

# Atmospheric Physics: Experiment meets Modelling

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## Introduction to stratospheric modelling: **Chemistry-Climate connections**

Martin Dameris

Deutsches Zentrum für Luft- und Raumfahrt (DLR)  
Institut für Physik der Atmosphäre, Oberpfaffenhofen, Germany

[martin.dameris@dlr.de](mailto:martin.dameris@dlr.de)



Knowledge for Tomorrow

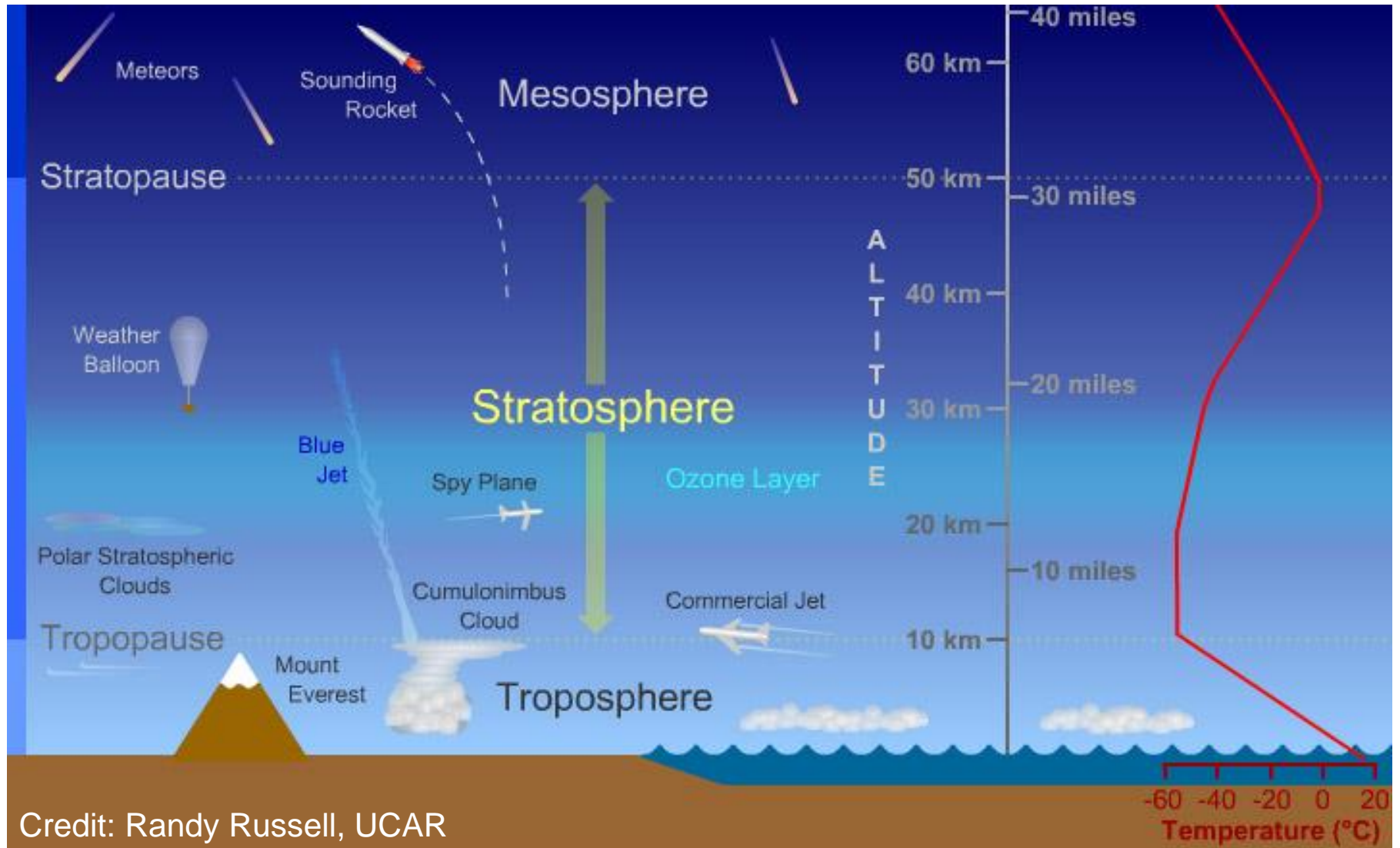
# Introduction to stratospheric modelling: **Chemistry-Climate connections**

## Outline

- What is the stratosphere?  
A short introduction
- Numerical models of the atmosphere
- Current research on chemistry-climate connections: Example of the stratospheric ozone layer

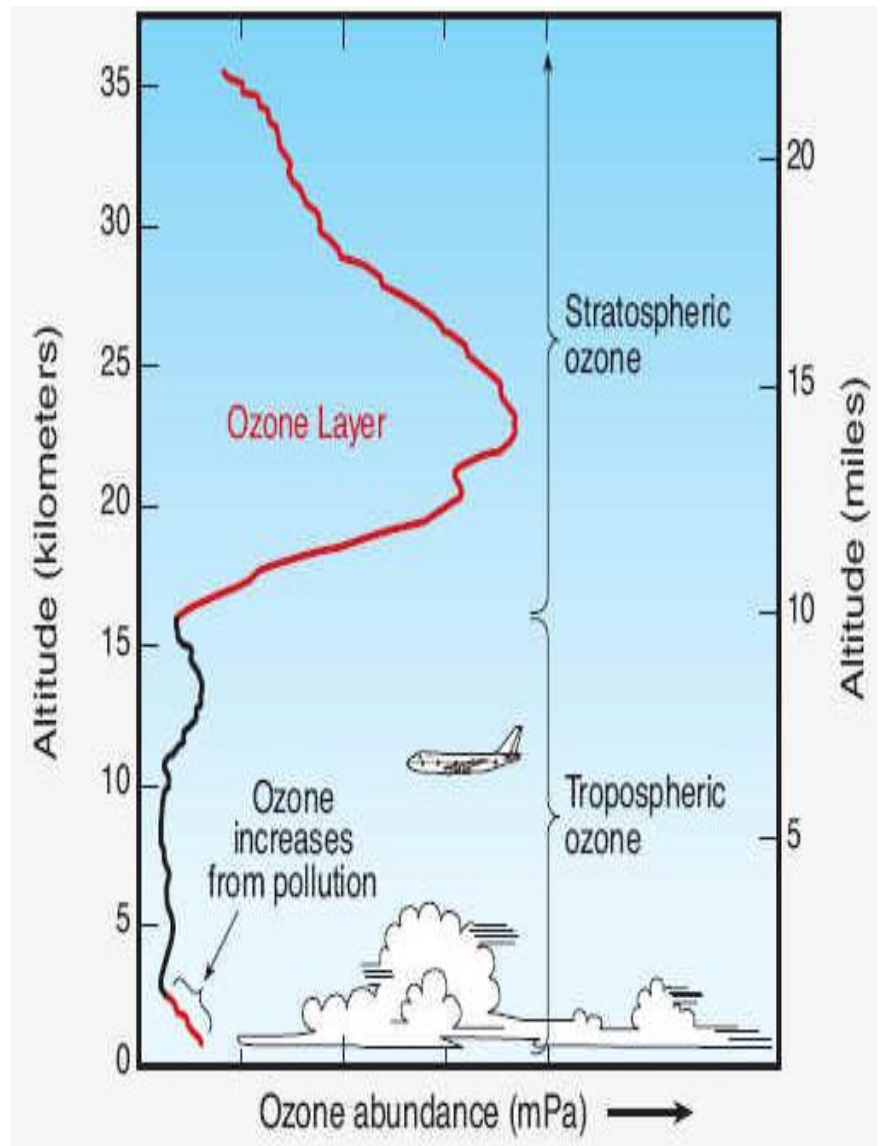
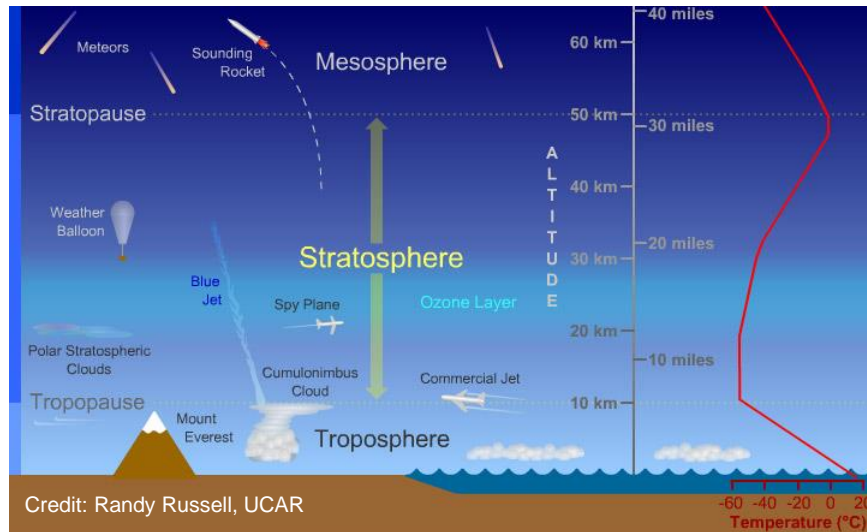


# The stratosphere

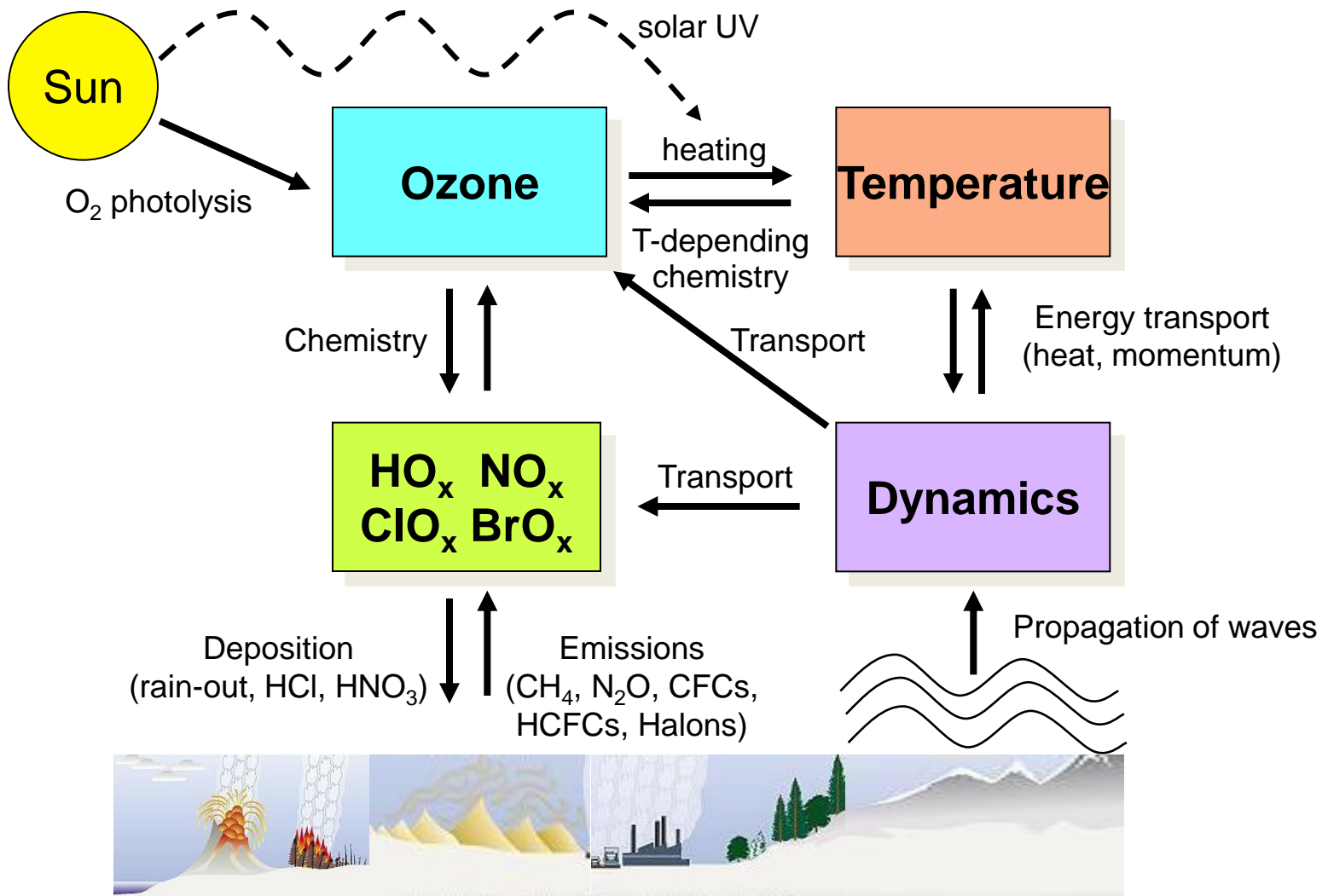




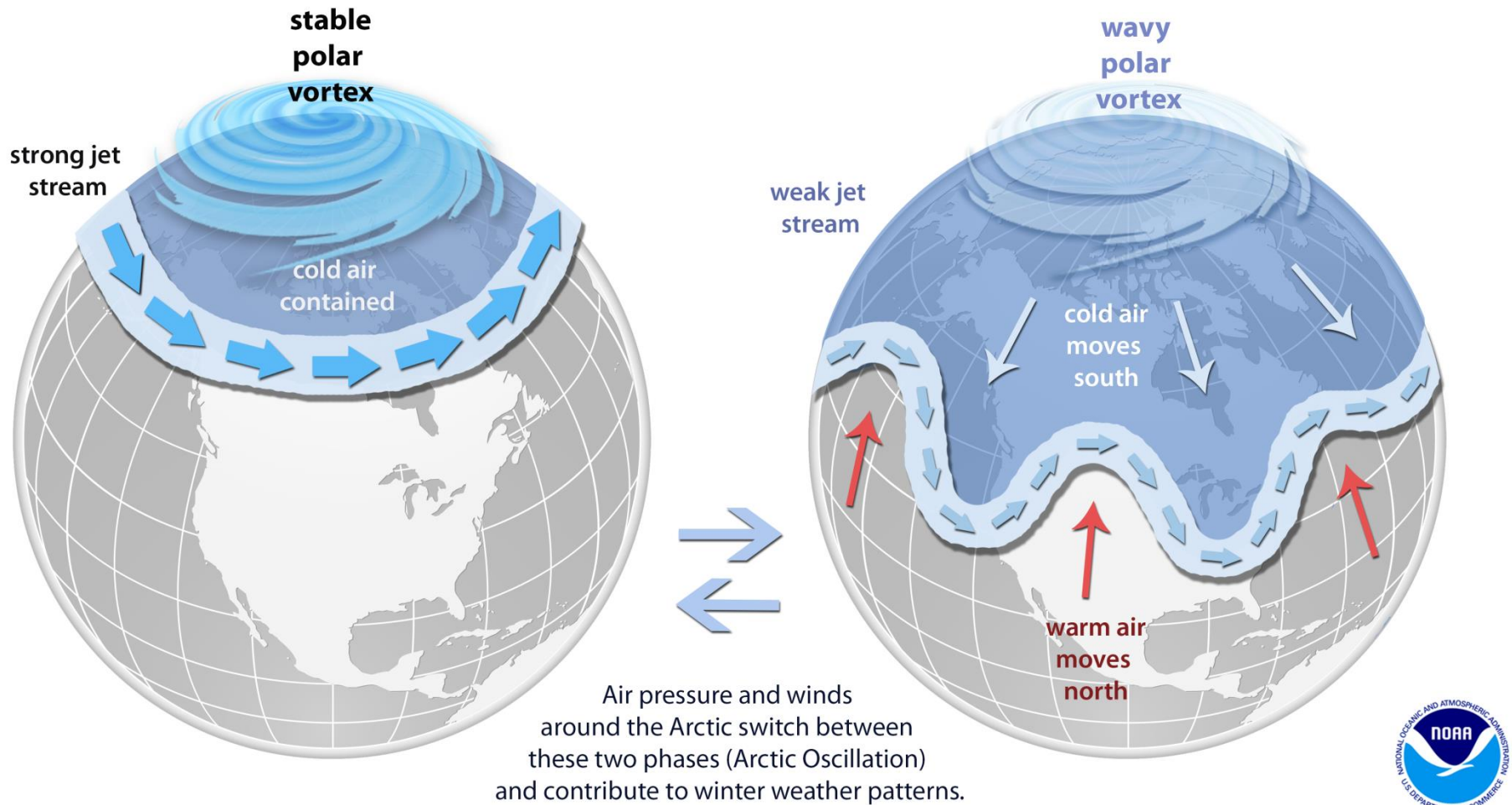
# The stratosphere



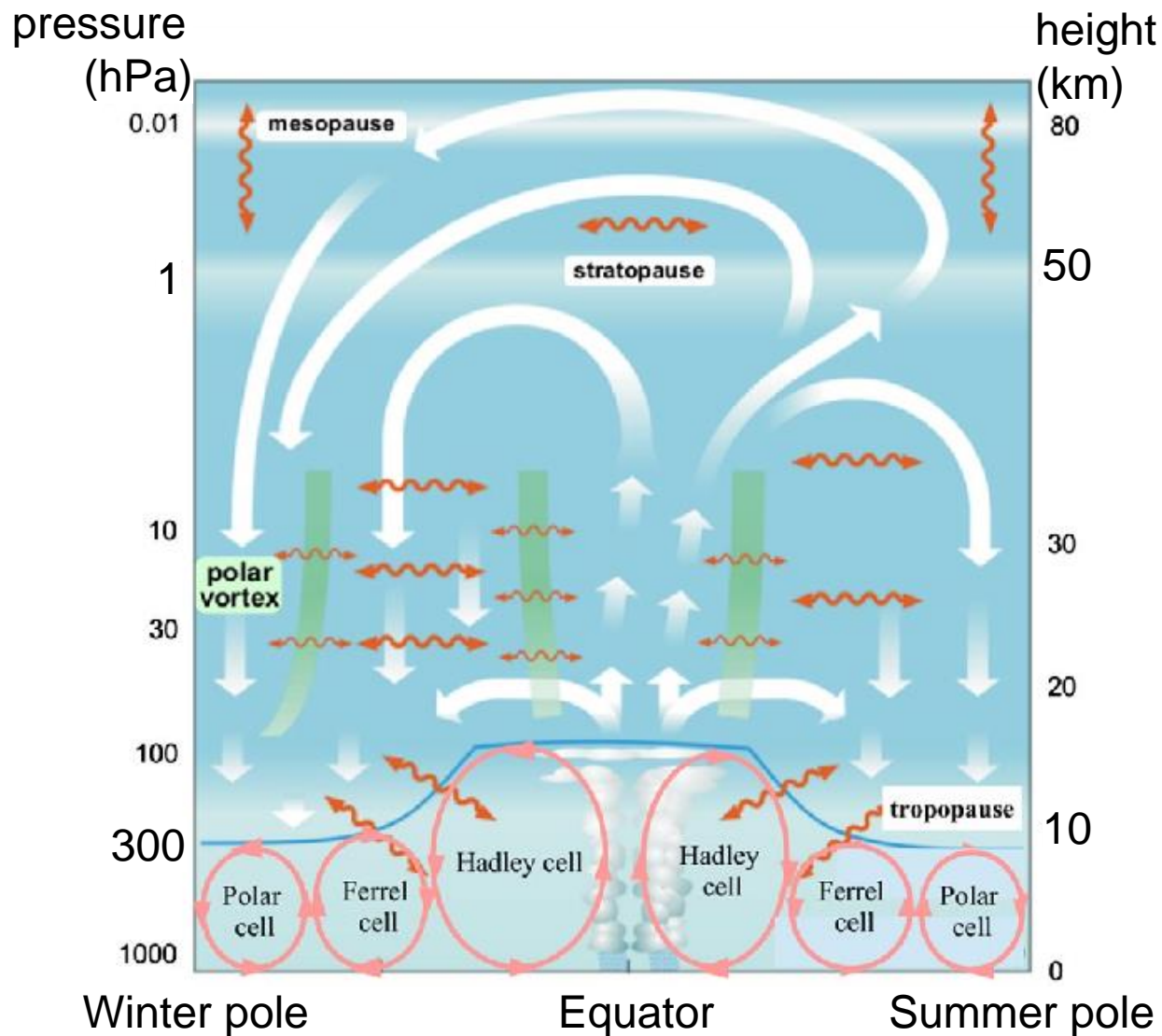
# Schematic of the stratospheric system



# The stratospheric Northern Hemisphere polar vortex in winter

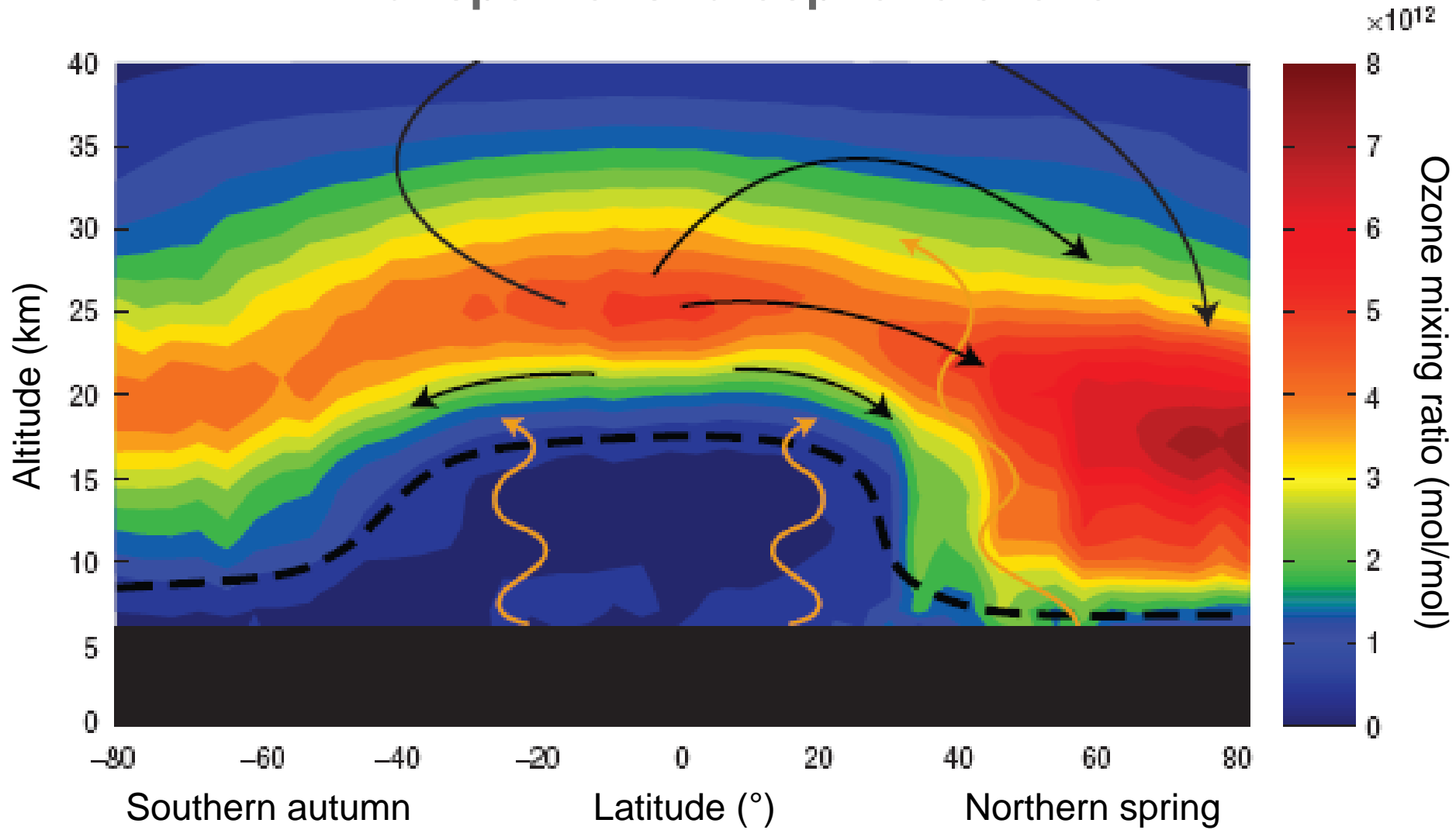


# The meridional circulation of the stratosphere





# Transport of stratospheric ozone



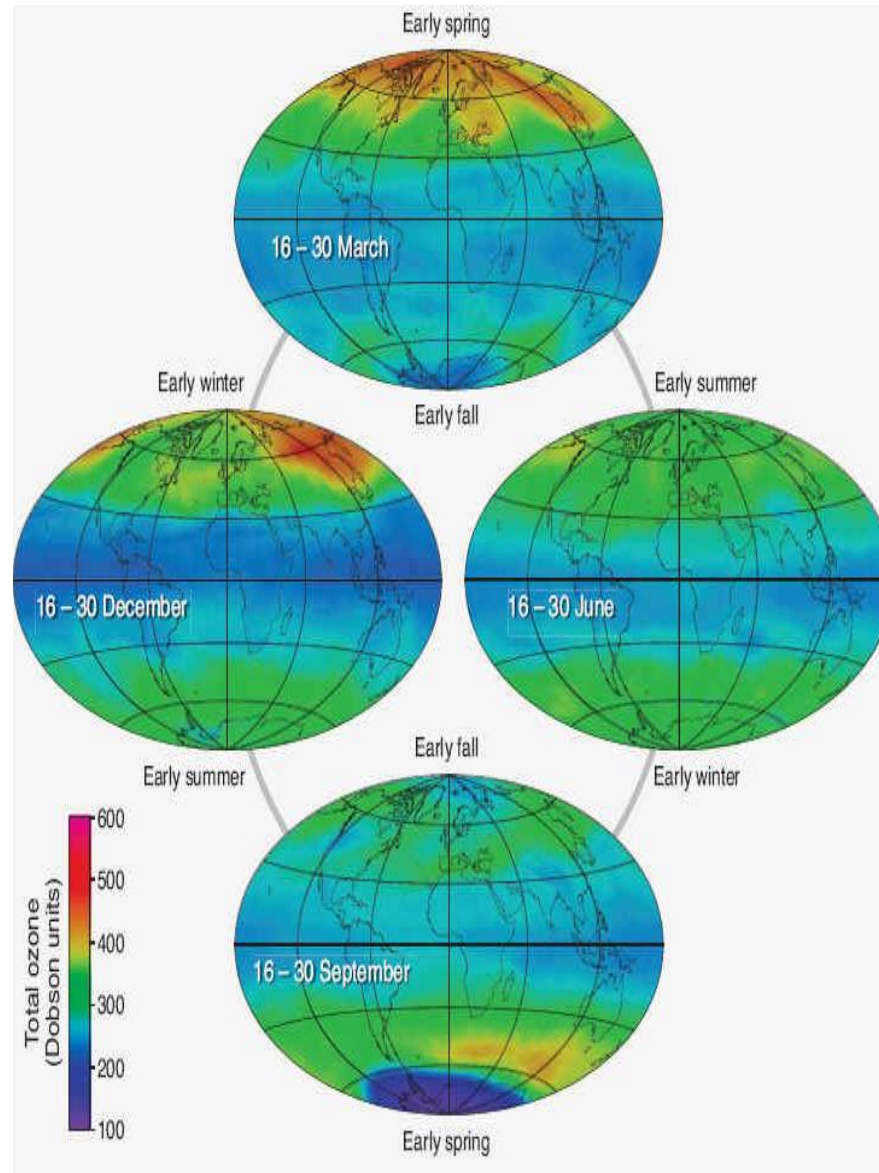
Shaw and Shepherd, 2007



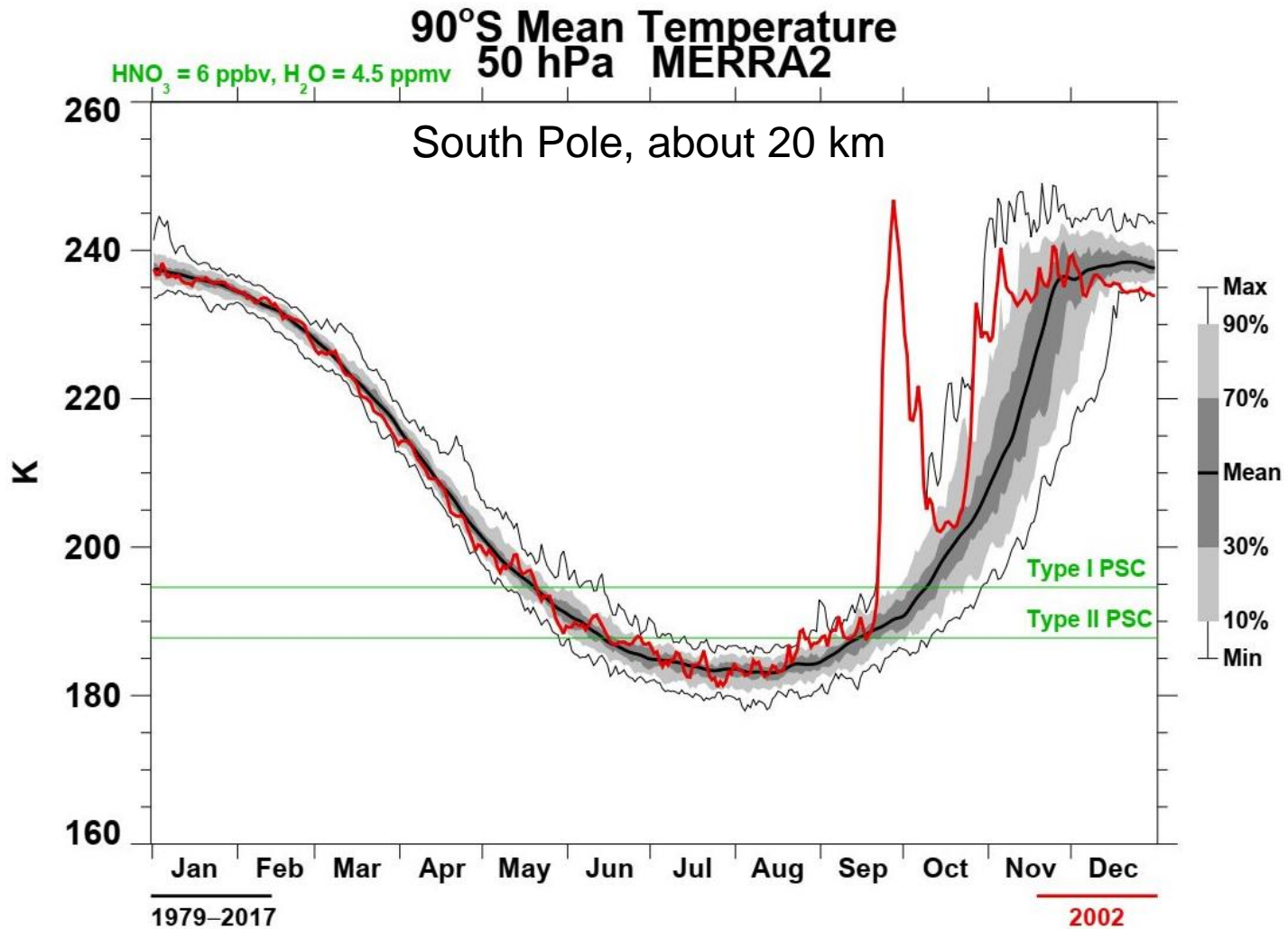


# Total ozone distribution for the four seasons

Example: 2009



# Variability of stratospheric dynamics

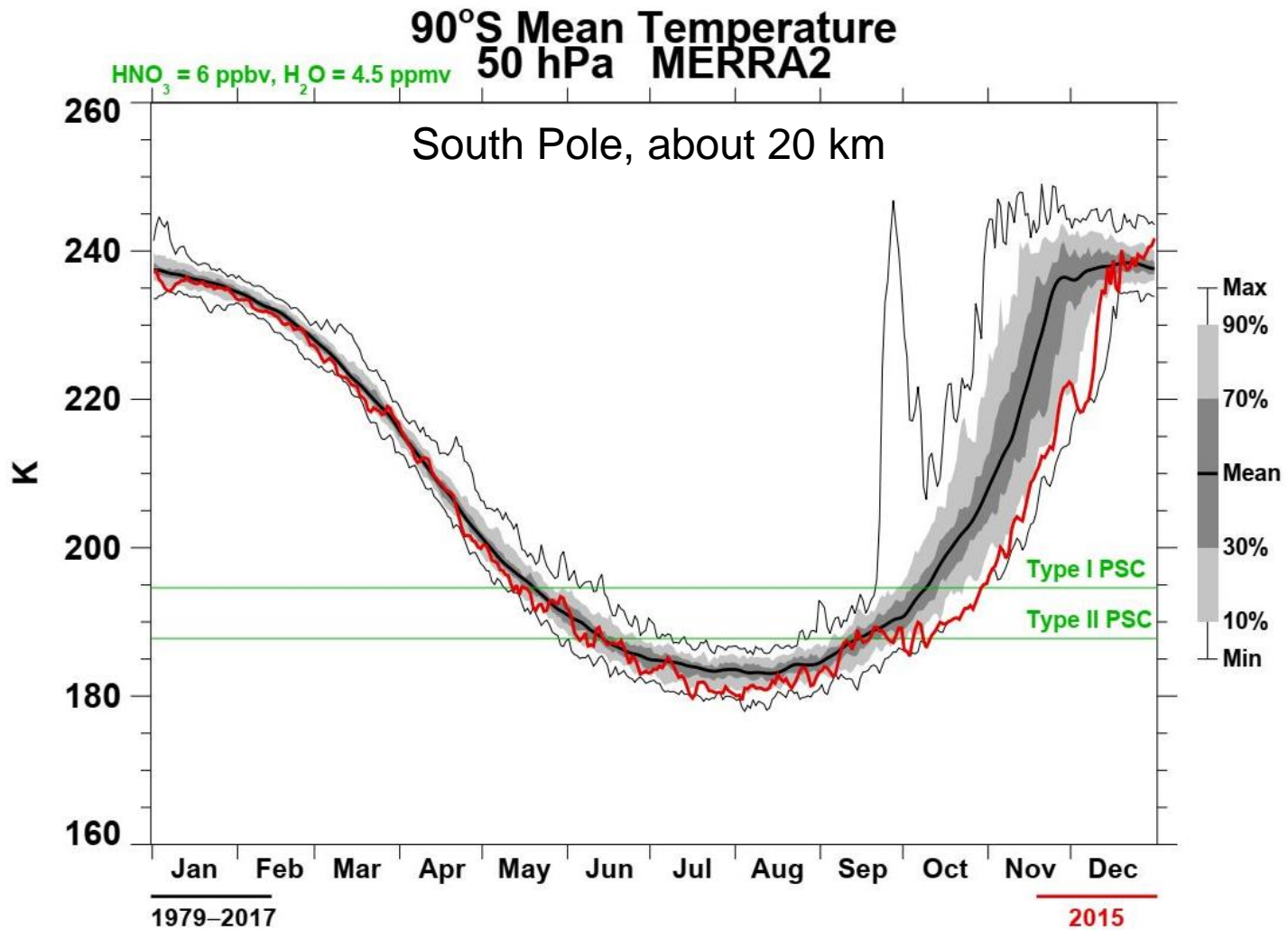


P. Newman (NASA), E. Nash (SSAI), S. Pawson (NASA)

2018-01-03T18:54:48Z



# Variability of stratospheric dynamics

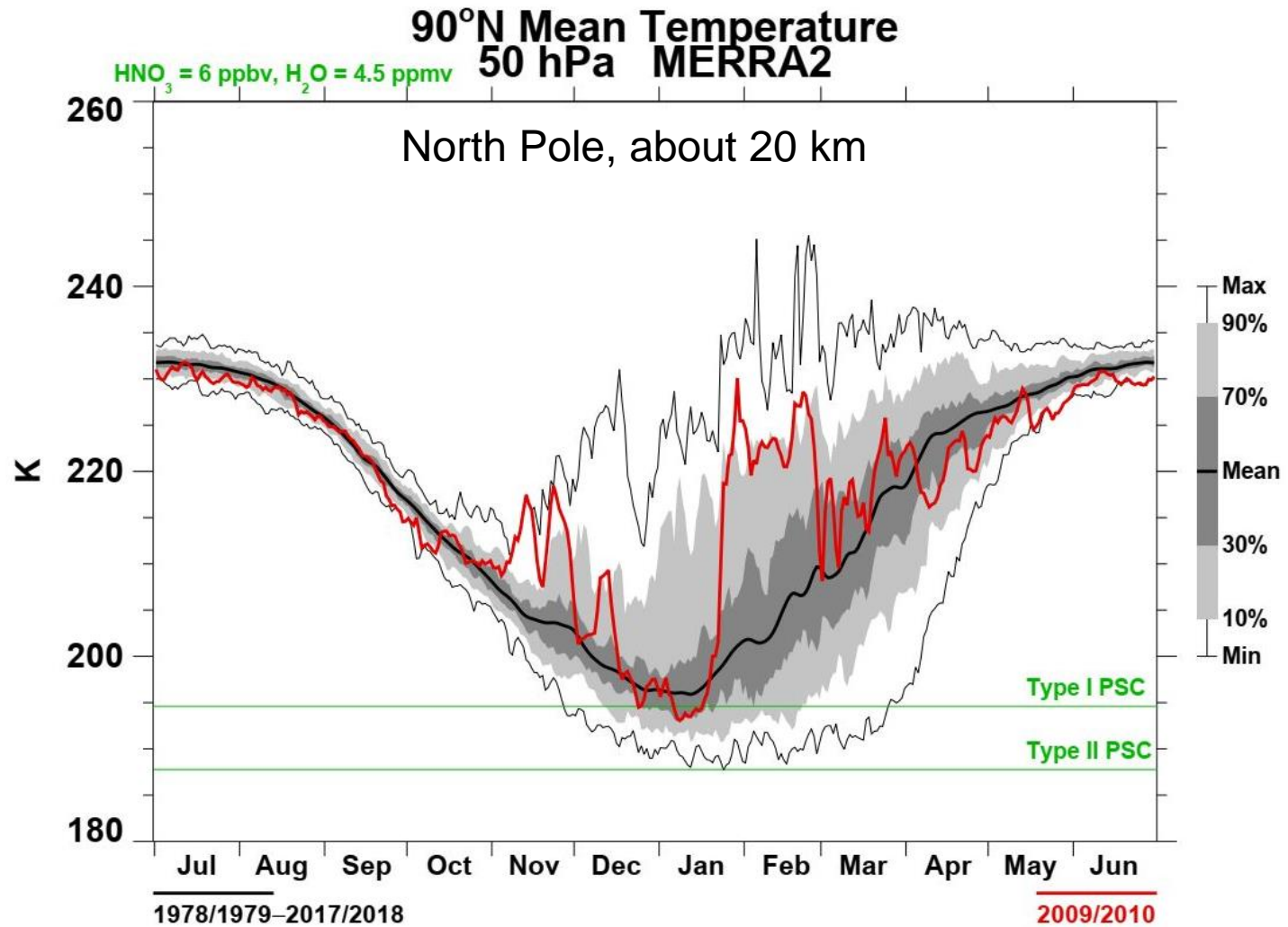


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# Variability of stratospheric dynamics



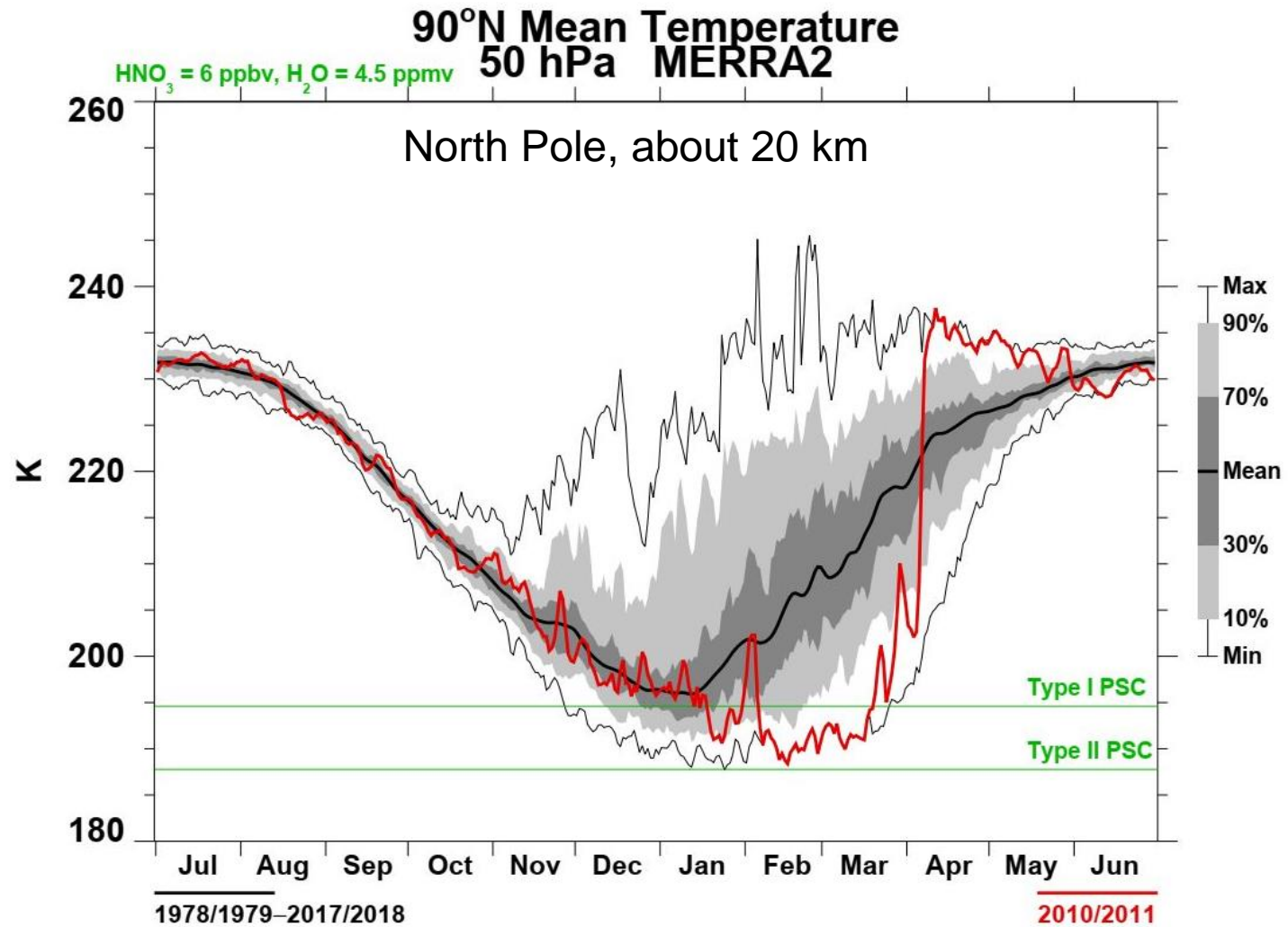
P. Newman (NASA), E. Nash (SSAI), S. Pawson (NASA)

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# Variability of stratospheric dynamics

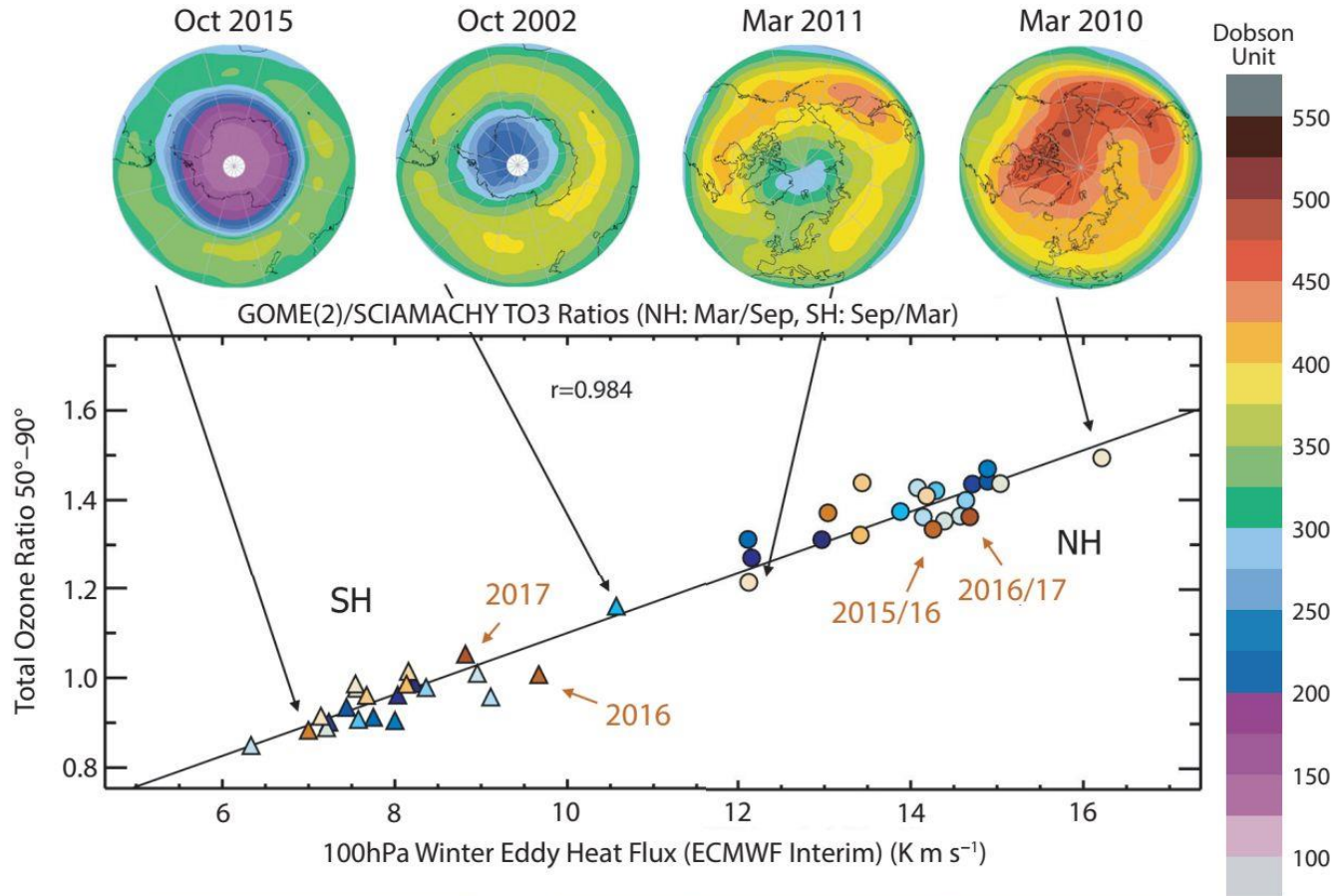


P. Newman (NASA), E. Nash (SSAI), S. Pawson (NASA)

2018-07-05T13:55:18Z



# Variability of polar ozone: Impact of stratospheric dynamics

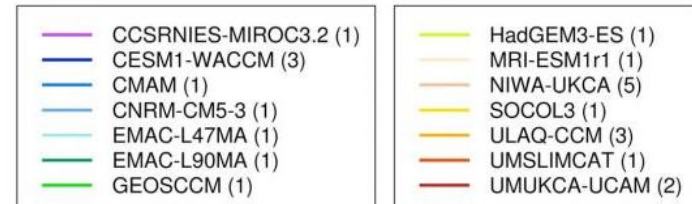
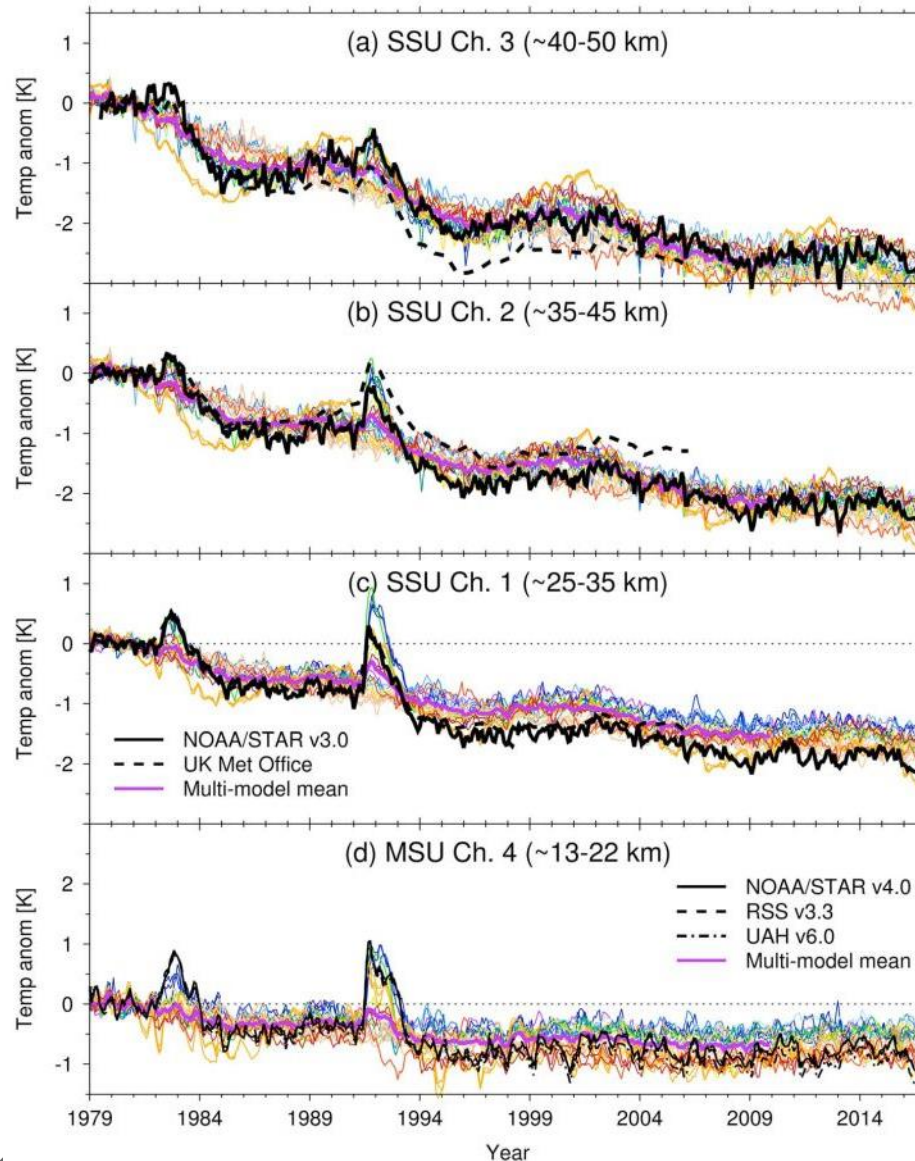


1996	1997	1998	1999	1995/1996	1996/1997	1997/1998	1998/1999
2000	2001	2002	2003	1999/2000	2000/2001	2001/2002	2002/2003
2004	2005	2006	2007	2003/2004	2004/2005	2005/2006	2006/2007
2008	2009	2010	2011	2007/2008	2008/2009	2009/2010	2010/2011
2012	2013	2014	2015	2011/2012	2012/2013	2013/2014	2014/2015
2016	2017			2015/2016	2016/2017		

WMO, 2019



# Recent stratospheric temperature changes

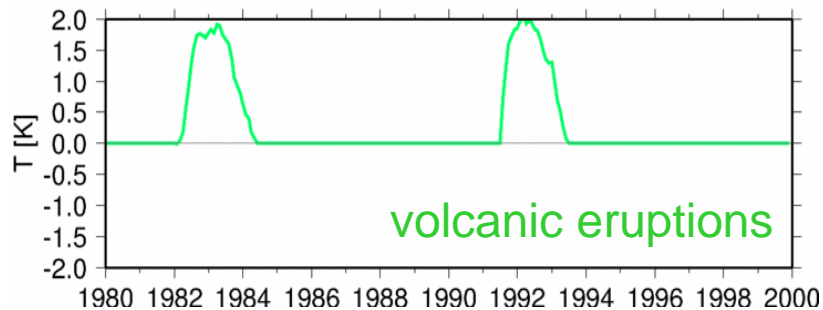
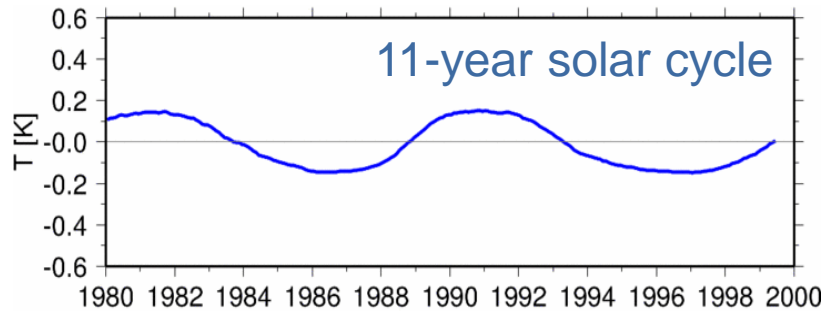
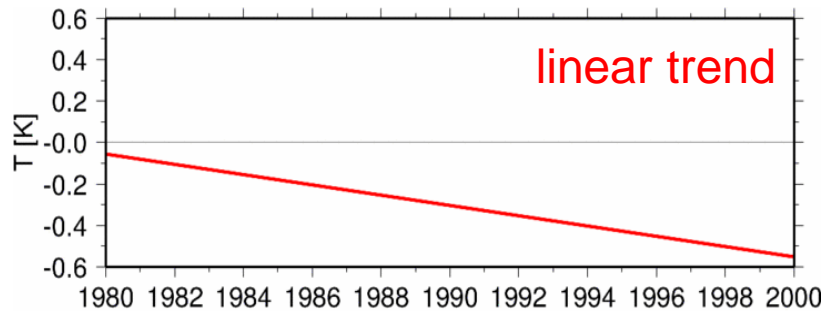


Maycock et al., 2018

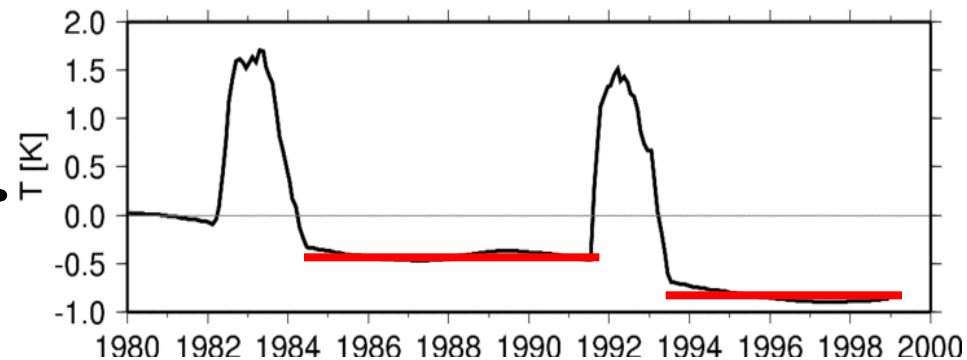




# Recent stratospheric temperature changes



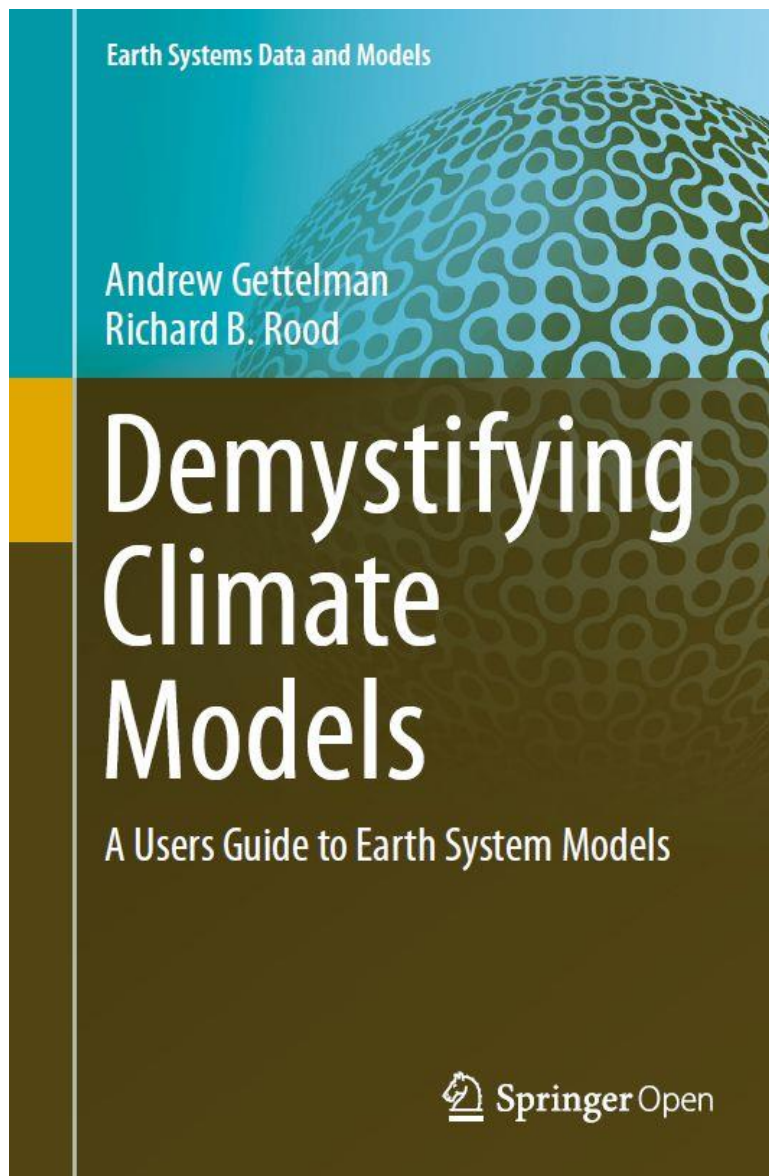
trend + solar cycle + volcanoes



⇒ „step-like" cooling of the stratosphere







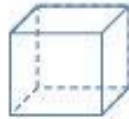
Freely  
available

<https://link.springer.com/book/10.1007/978-3-662-48959-8>



# Dimensions of atmospheric models

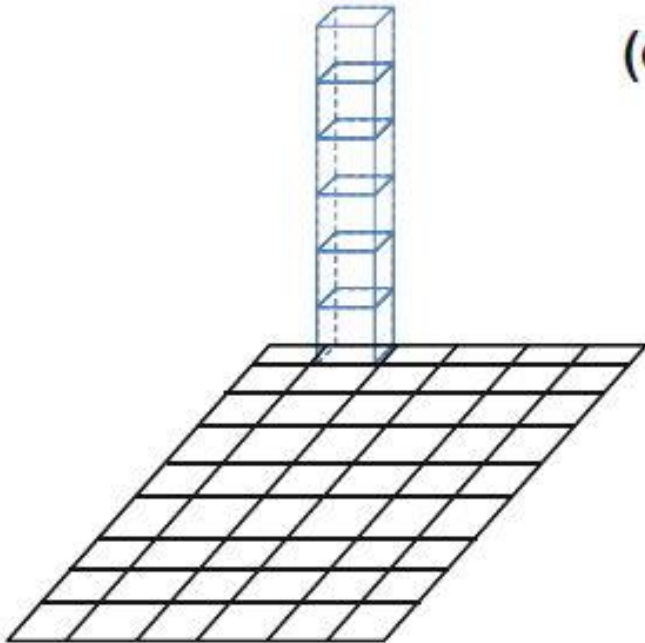
- (a)** Zero dimensions  
(one point):  
boxmodel



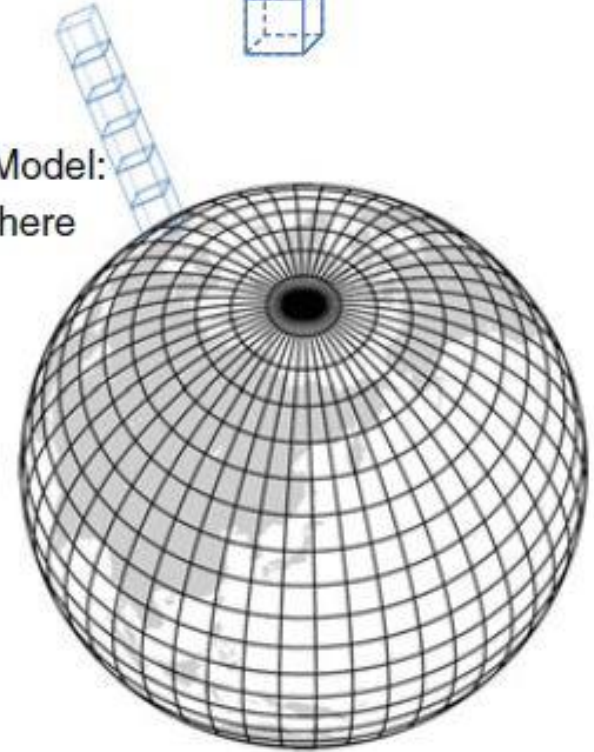
- (b)** One dimension  
(height or depth):  
a column of grid cells



- (c)** Two horizontal dimensions  
(+ one vertical dimension) = 3D:  
a grid of columns

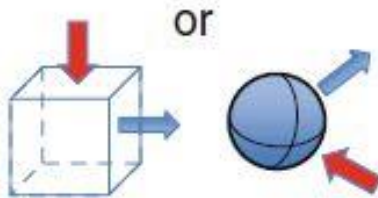


- (d)** 3D General Circulation Model:  
a grid of columns on a sphere

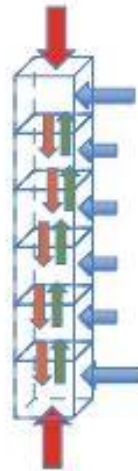


# Hierarchy of atmospheric models

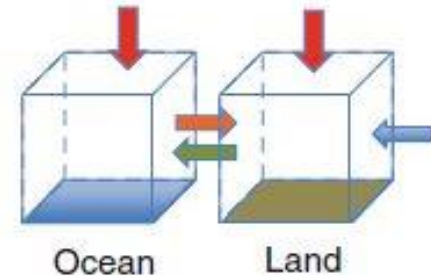
**(a) Box Model**



**(b) Single Column**

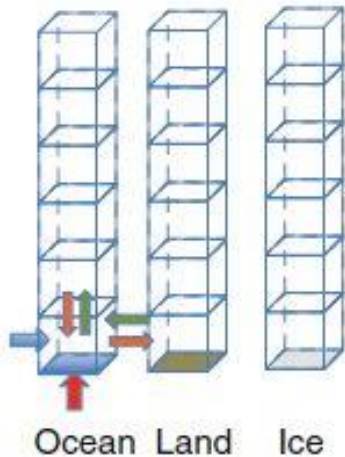


**(c) Two-Box Model**

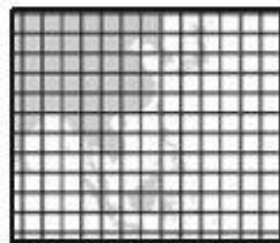


$$X_i = A + B + C - D$$

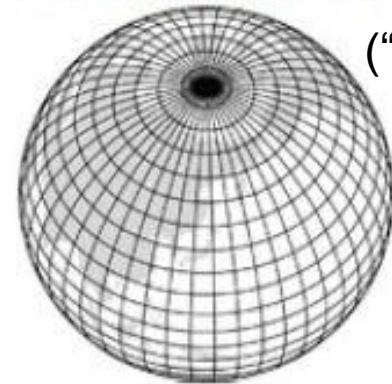
**(d) Multiple-Column  
(Intermediate Complexity)**



**(e) Limited Area  
(Regional Model)**



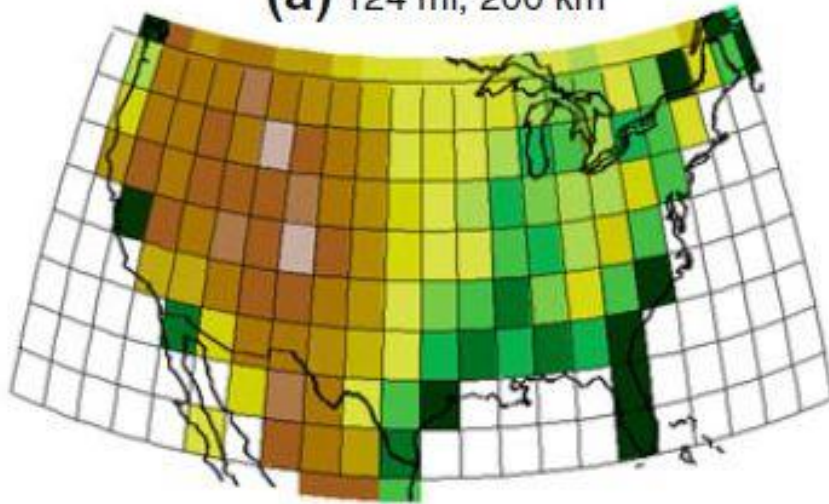
**(f) Global Grid  
General Circulation Model  
("GCM")**



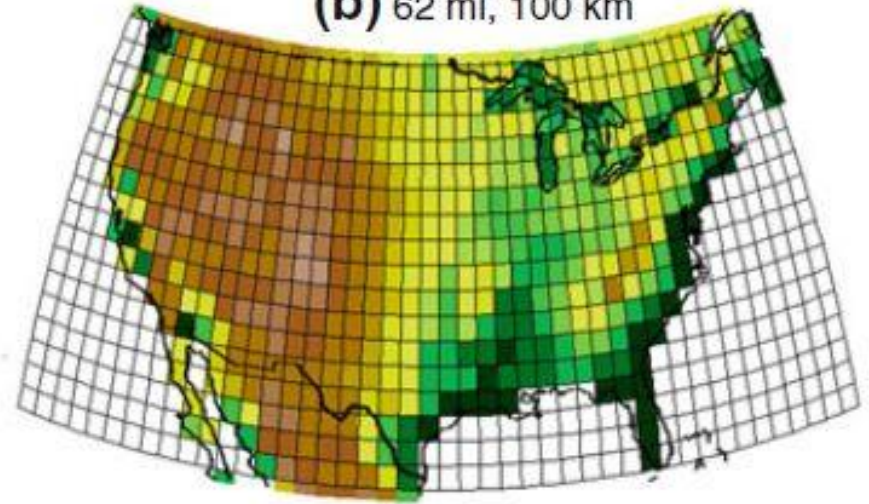


# Horizontal resolution of regional and global models

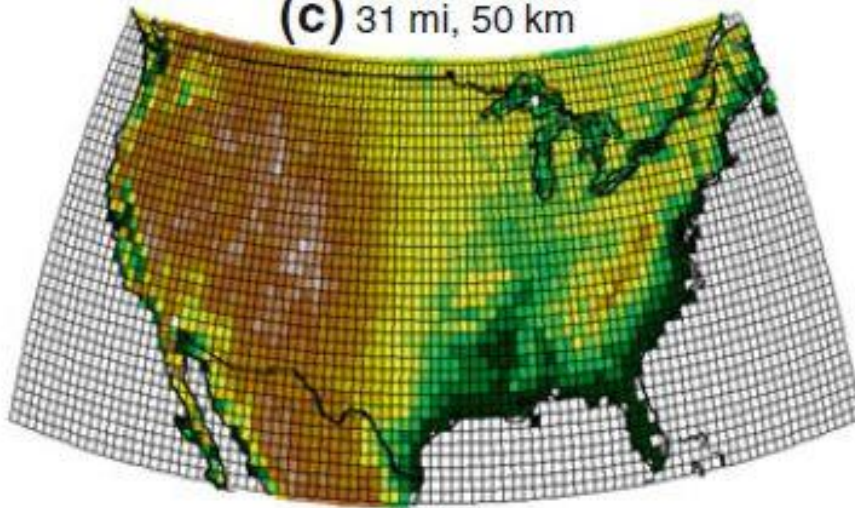
(a) 124 mi, 200 km



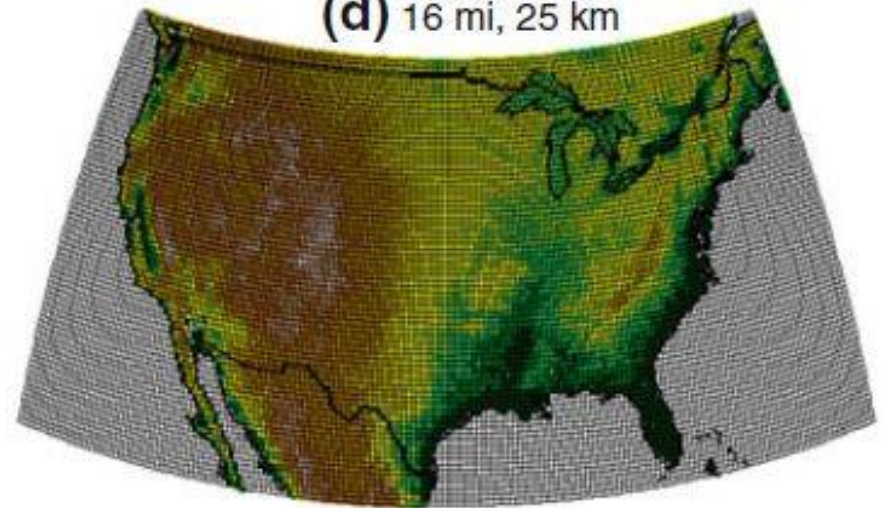
(b) 62 mi, 100 km



(c) 31 mi, 50 km

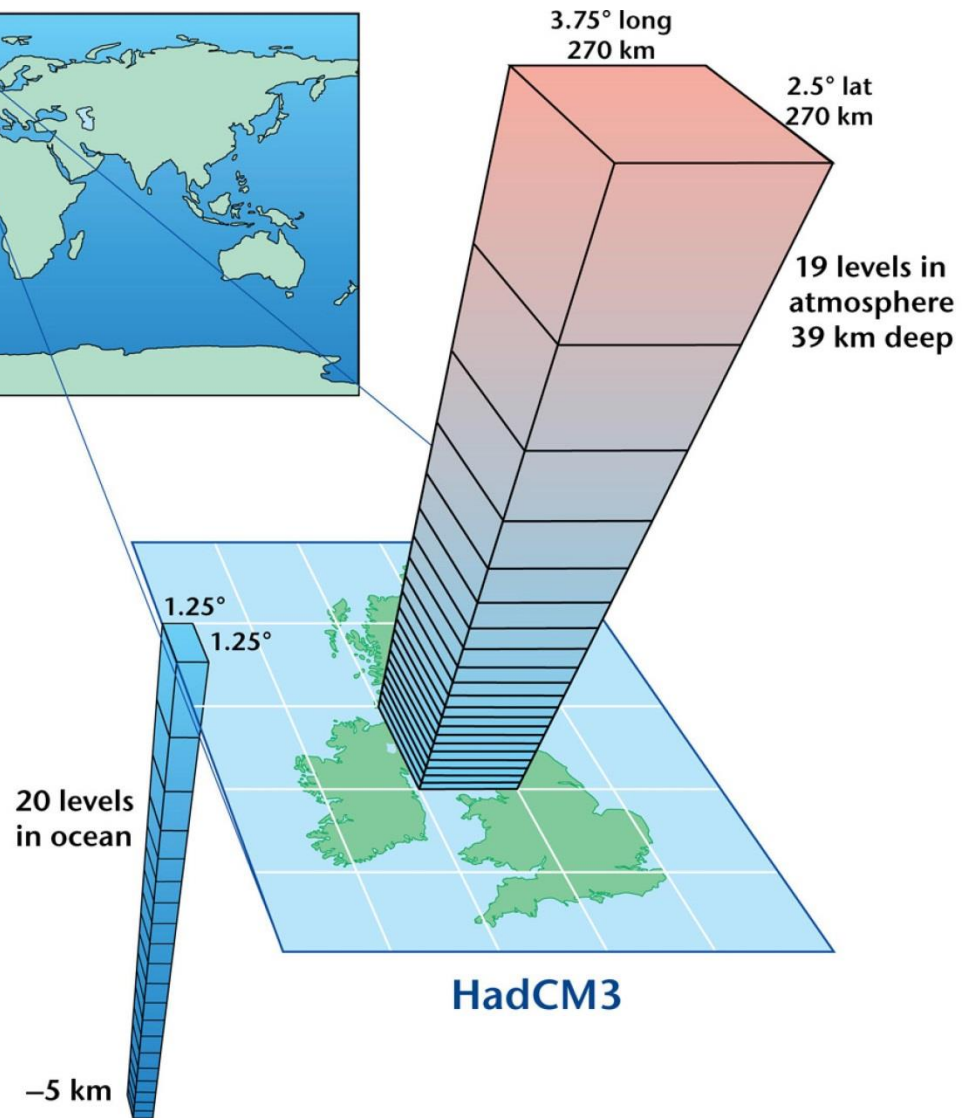
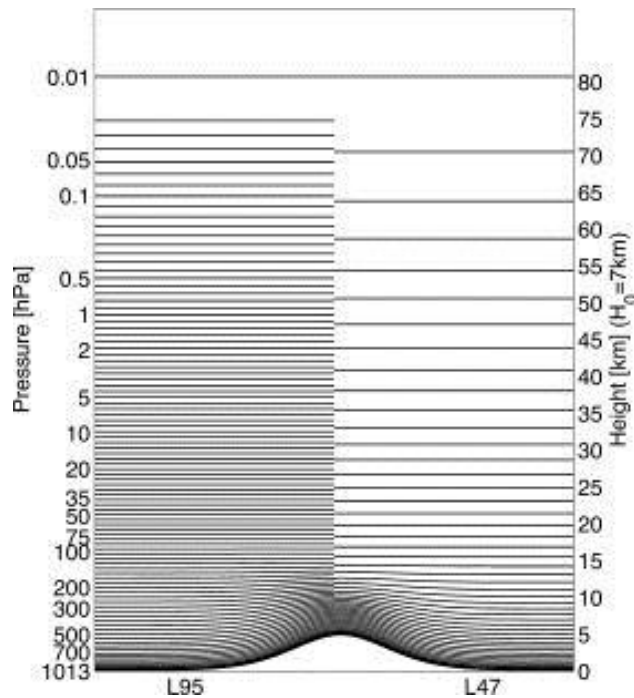
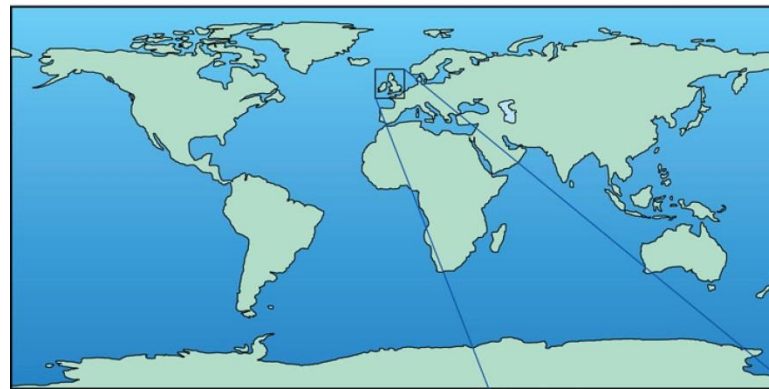


(d) 16 mi, 25 km

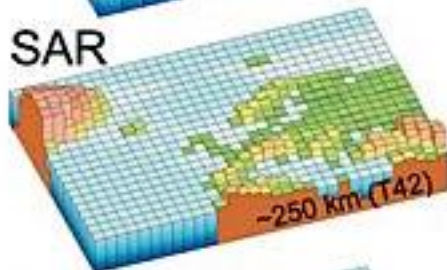
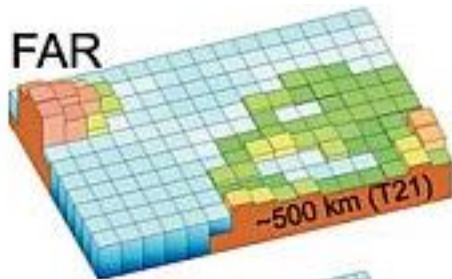




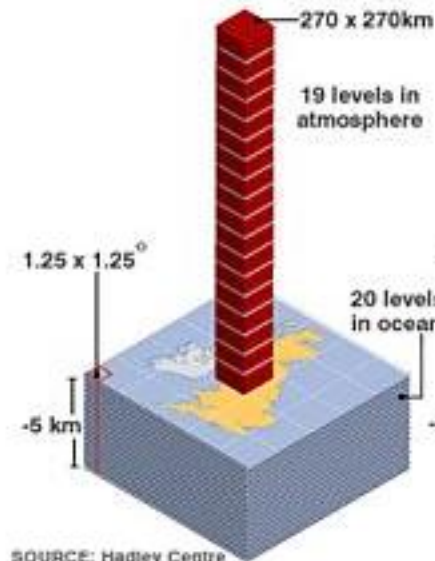
# Vertical resolution of GCM and climate models



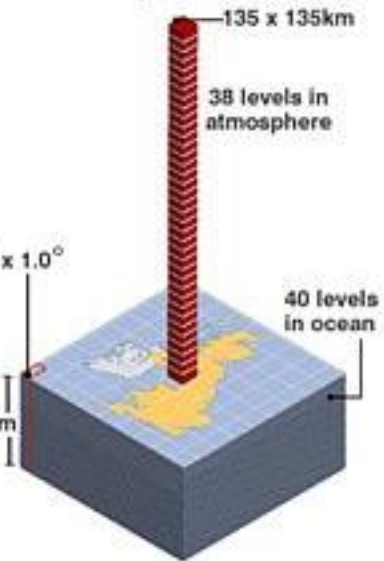
# History of (global) climate models incl. GCM



**PROGRESSION OF CLIMATE MODELS**  
1990s



**Present day**



SOURCE: Hadley Centre

**AR5:** ~70km maximum horizontal resolution; up to 90 layers in the atmosphere and over 60 in the ocean.



# Definition

## ***Atmospheric Model***

Numerical models are useful for investigations of the composition and the thermal and dynamical structure of Earth's atmosphere. They allow evaluation of different processes and mechanisms as well as feedbacks. Scientific progress can be achieved by understanding the discrepancies between observations and results derived from model simulations. Assessments of the future development of atmospheric dynamics and chemistry are typically based on ***scenario simulations*** and ***sensitivity studies***.



# Definition

## ***Atmospheric General Circulation Model (AGCM)***

*Three-dimensional model of large-scale (spatial resolution of a few hundred km) physical, radiative, and dynamical processes in the atmosphere over years and decades.*

An AGCM is used to study changes in natural variability of the atmosphere and for investigations of climate effects of radiatively active trace gases (greenhouse gases) and aerosols (natural and anthropogenic), along with their interactions and feedbacks.





# Definition

## ***Atmospheric General Circulation Model (AGCM)***

*Three-dimensional model of large-scale (spatial resolution of a few hundred km) physical, radiative, and dynamical processes in the atmosphere over years and decades.*

Usually, AGCM calculations employ prescribed concentrations of radiatively active gases, e.g., carbon dioxide ( $\text{CO}_2$ ), methane ( $\text{CH}_4$ ), nitrous oxide ( $\text{N}_2\text{O}$ ), chlorofluorocarbons (CFCs), and ozone ( $\text{O}_3$ ). Changes of water vapor ( $\text{H}_2\text{O}$ ) concentrations due to the hydrological cycle are directly simulated by an AGCM. Sea surface temperatures (SSTs) are prescribed.

This means that neither a chemistry model nor an ocean model is interactively coupled to an AGCM.



# Definition

## ***Chemical Transport Model (CTM)***

*Simulation of chemical processes in the atmosphere employing meteorological analyses derived from observations or AGCMs.*

A CTM is a *non-interactive* model that does not consider the feedback of chemistry to dynamical and radiative processes. It uses winds and temperatures from meteorological analyses or predictions to specify the atmospheric transport and temperatures and to calculate the abundances of chemical species in the troposphere and stratosphere. A CTM can be used to simulate the evolution of atmospheric composition and help interpret observations.



# Definition

## ***Climate Model***

An AGCM interactively coupled to an ocean model, commonly referred to as an AOGCM or a climate model, is used for investigation of climate change. More recently, climate models may also include other feedback processes (e.g., carbon cycle, interaction with the biosphere). These are so-called ***Earth-System Models***.



# Definition

## ***Chemistry-Climate Model (CCM)***

*An AGCM or climate model that is interactively coupled to a detailed chemistry module.*

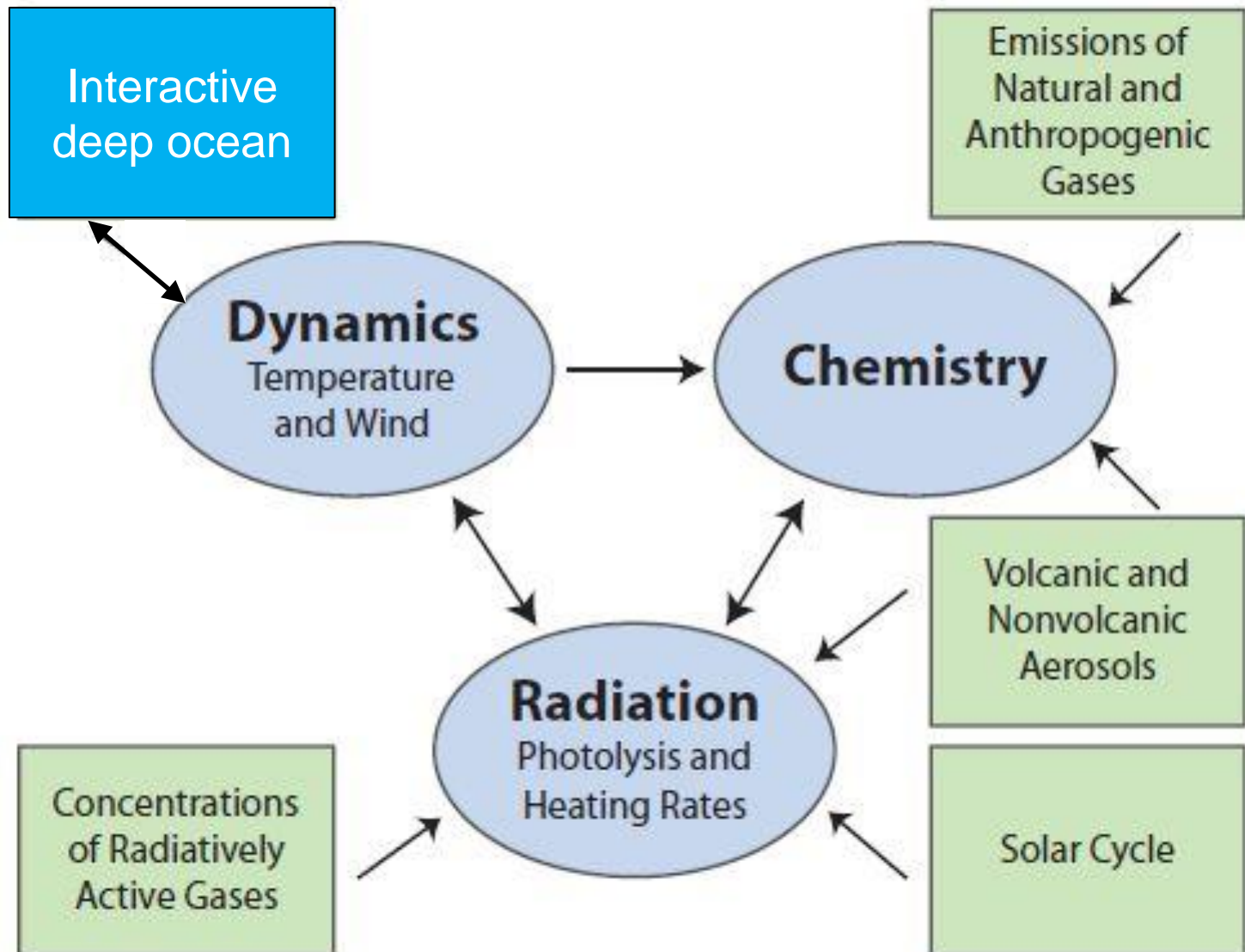
In a CCM, the simulated concentrations of the radiatively active gases are used in the calculations of net heating rates.

Changes in the abundance of these gases due to chemistry and advection influence heating rates and, consequently, variables describing atmospheric dynamics such as temperature and wind. This gives rise to a dynamical-chemical coupling in which the chemistry influences the dynamics (via radiative heating) and vice versa (via temperature and advection).





# Schematic of a CCM



# Strategy of climate modelling

So-called ***transient simulations*** consider observed or predicted gradual changes in concentrations of radiatively active gases and other boundary conditions (e.g., emissions). The temporal development of source gas emissions are prescribed for a specific episode (years to decades).

In so-called ***time-slice simulations***, the internal variability of a CCM can be investigated under fixed conditions, e.g., for greenhouse gas (GHG) concentrations and SSTs, to estimate the significance of specific changes.



# Strategy for CCM simulations for IPCC and WMO

Three types of numerical model simulations covering the middle atmosphere and troposphere have been defined, as recommended by CCMI:

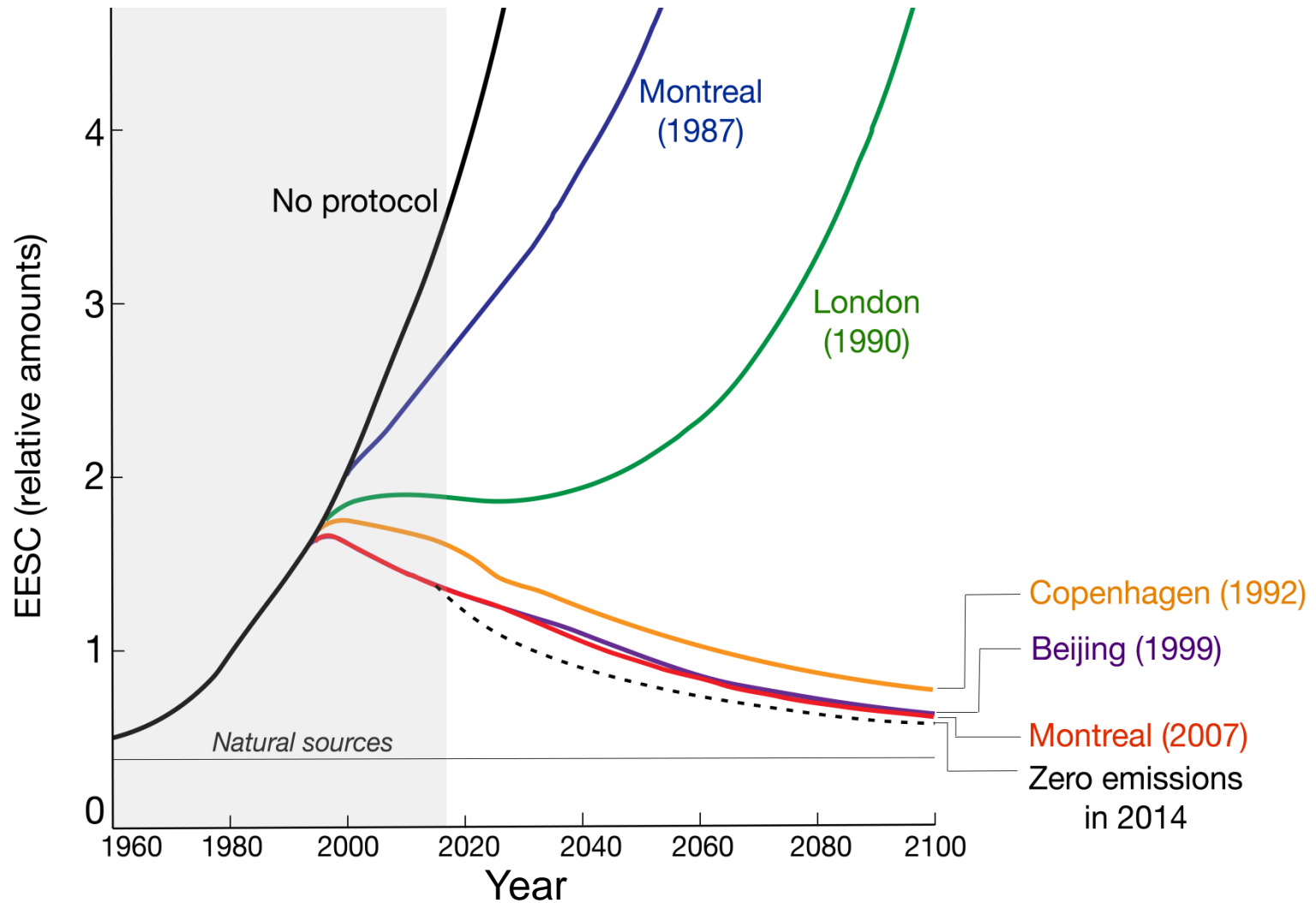
- (1) A hindcast simulation with specified dynamics, i.e. nudged to observed meteorology from 1979 to 2017 (referred to [REF-C1SD](#)),
- (2) a free-running hindcast simulation representing the past (from 1950 to 2017; referred to [REF-C1](#)), and
- (3) a combined hindcast and forecast simulation (from 1950 until 2100; referred to [REF-C2](#) (RCP-6.0) either with fixed ocean temperature (SST) and sea-ice cover (SIC) or with an interactively coupled ocean).

In addition, several [sensitivity simulations](#) have been carried out, for instance with fixed boundary conditions regarding ozone depleting substances (ODSs) and greenhouse gases (GHGs).





# Equivalent Effective Stratospheric Chlorine (EESC)

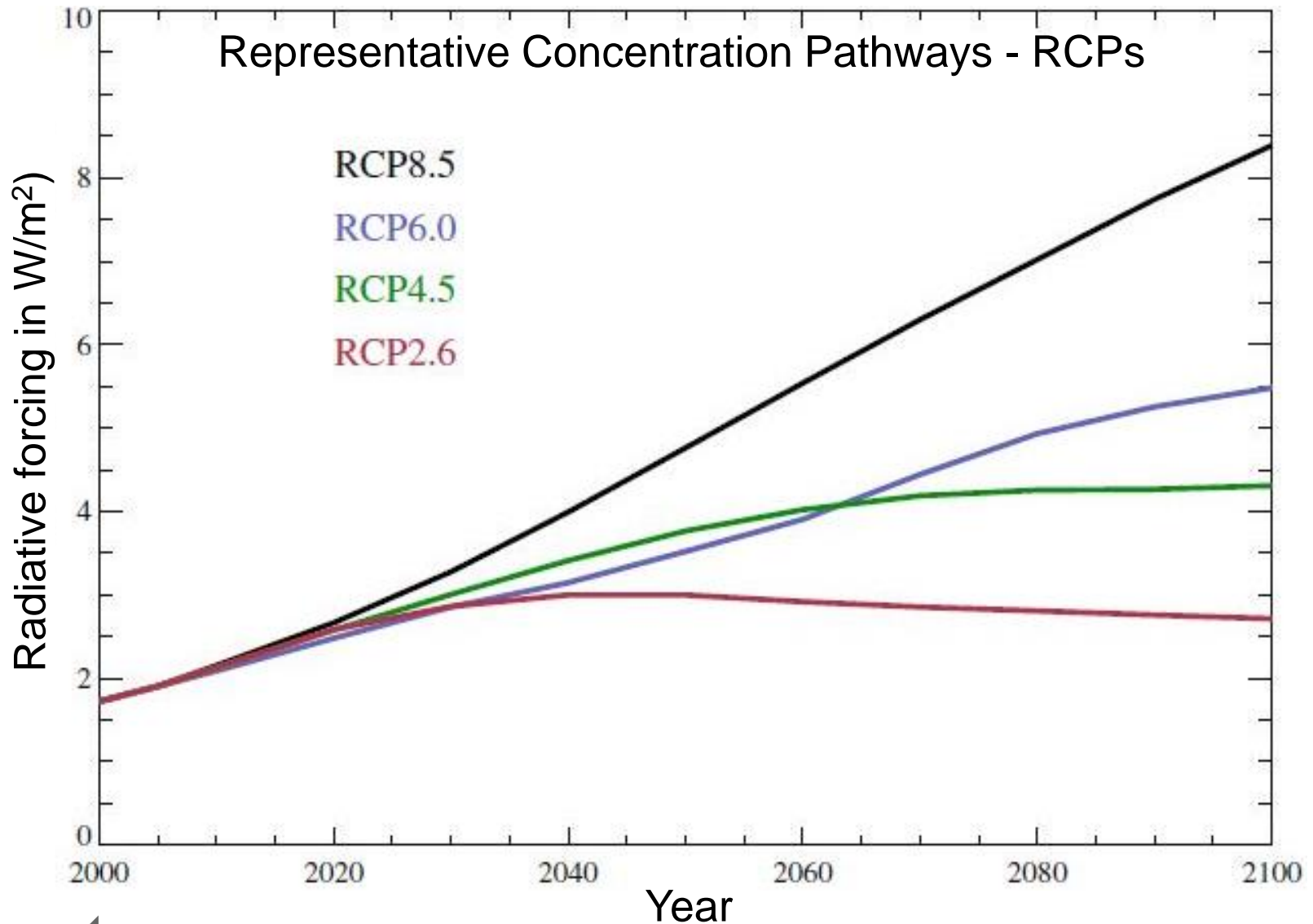


Source: Montreal Protocol Scientific Assessment Panel (2014). Twenty Questions and Answers About the Ozone Layer. The data visualization is available at [OurWorldinData.org](https://www.ourworldindata.org). There you will find more on this topic.

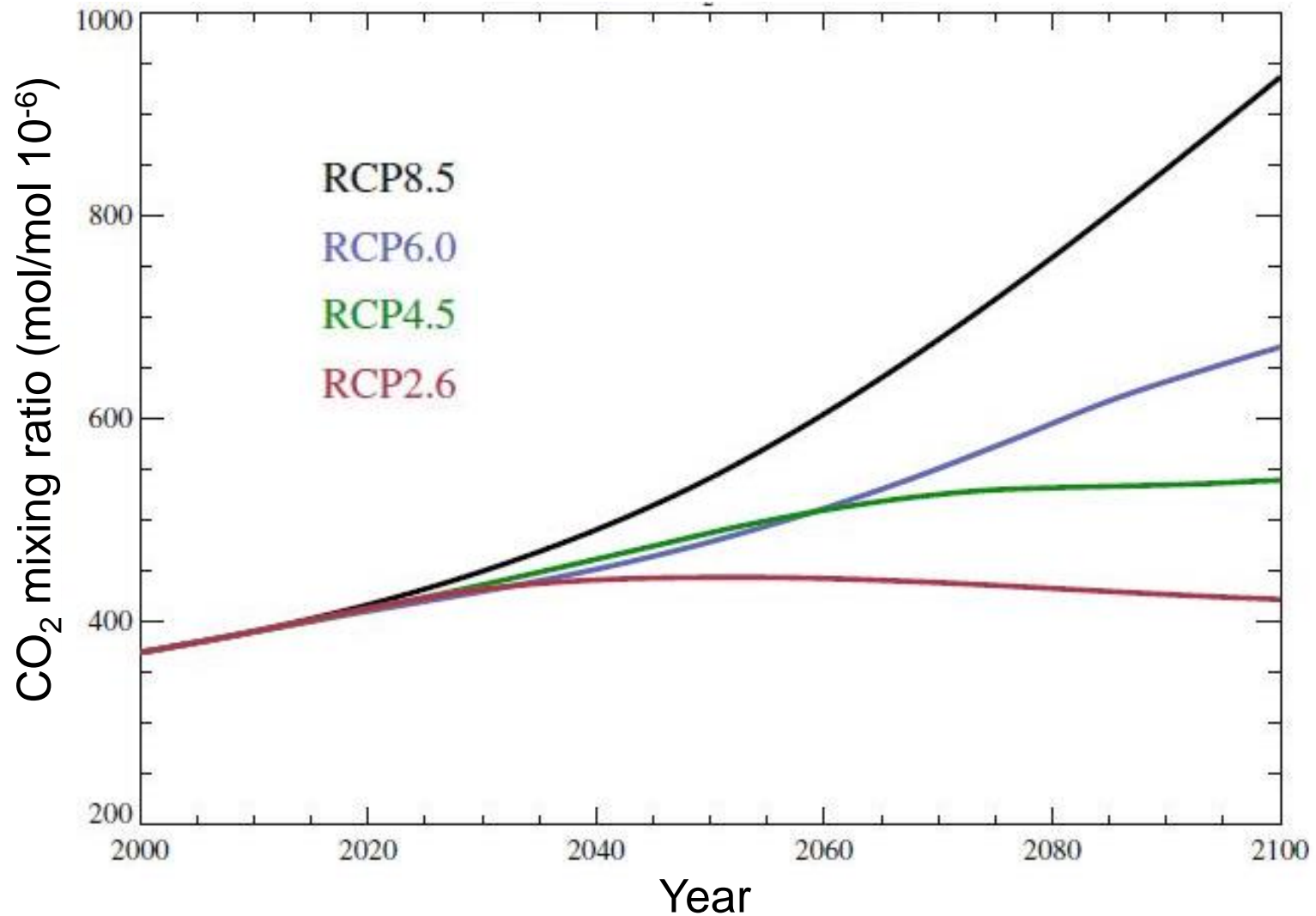
Licensed under CC-BY-SA by the authors.



# Future scenarios of radiative forcing ( $\text{W/m}^2$ )



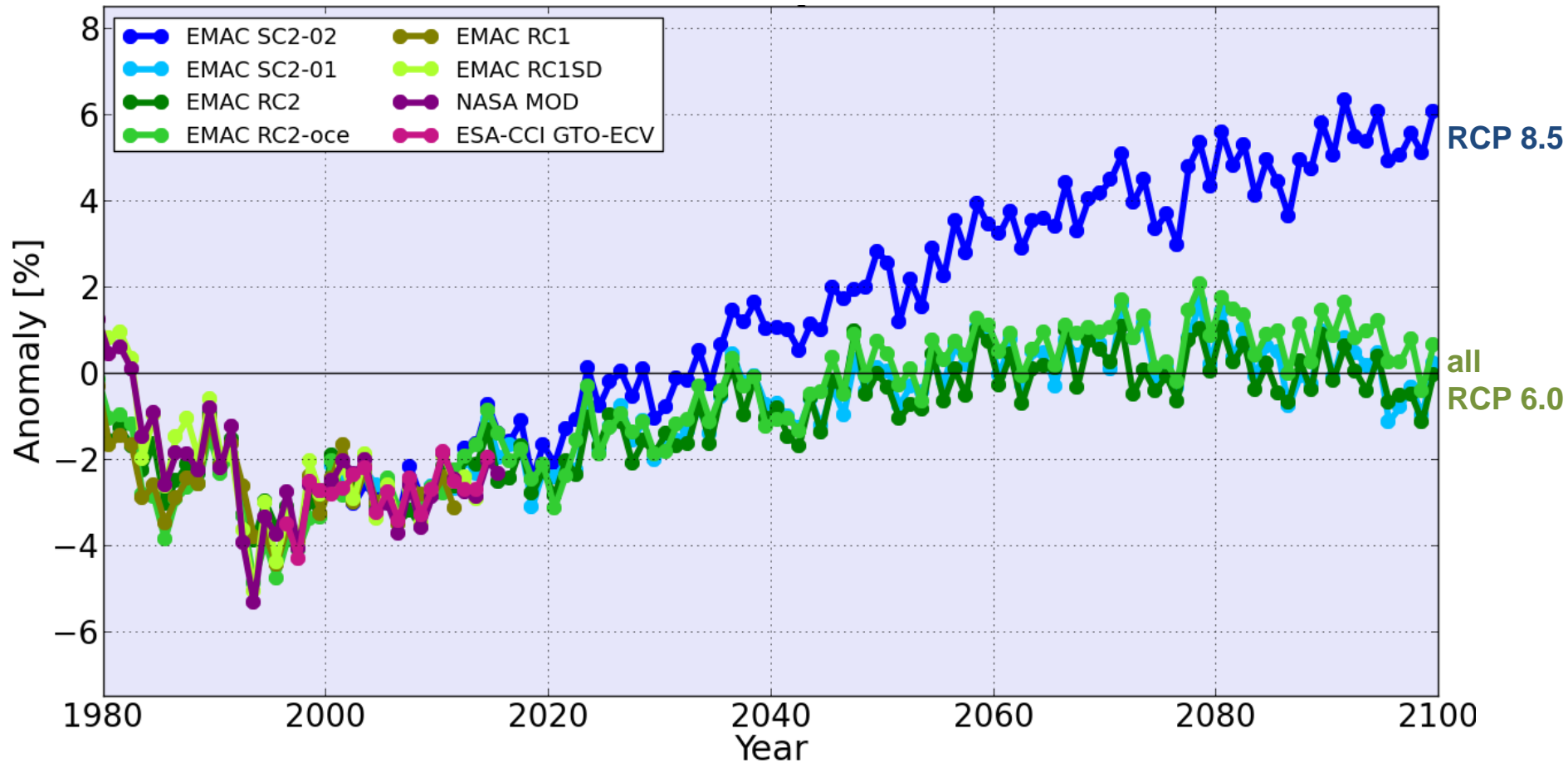
# Scenarios for future CO<sub>2</sub> mixing ratio (mol/mol 10<sup>-6</sup>)





# Ozone anomalies (1960-2100): 60°S - 60°N

Comparison of satellite- and CCM-data (EMAC) incl. projections

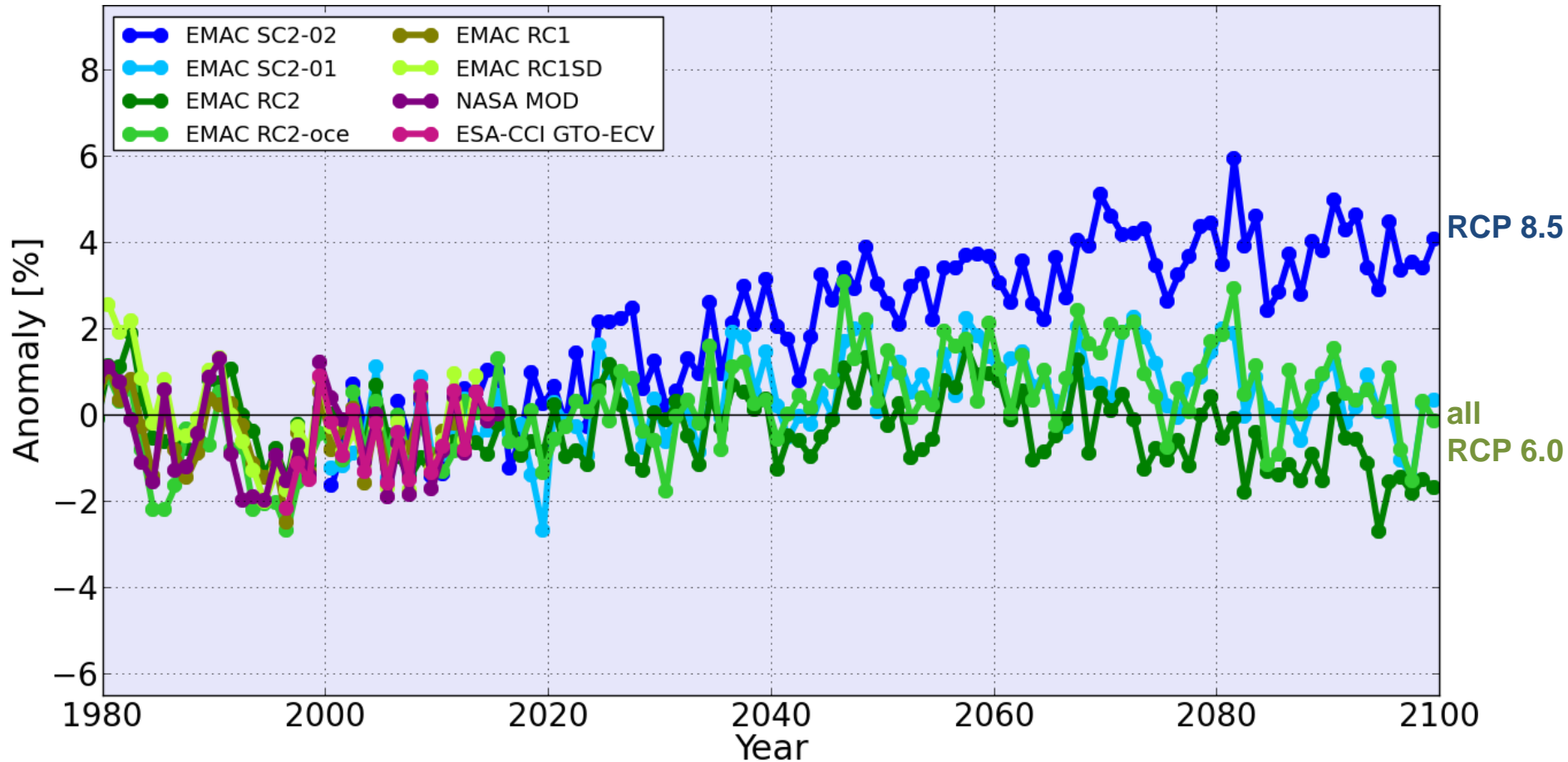


update of Jöckel et al., 2016



# Ozone anomalies (1960-2100): 20°S - 20°N

Comparison of satellite- and CCM-data (EMAC) incl. projections

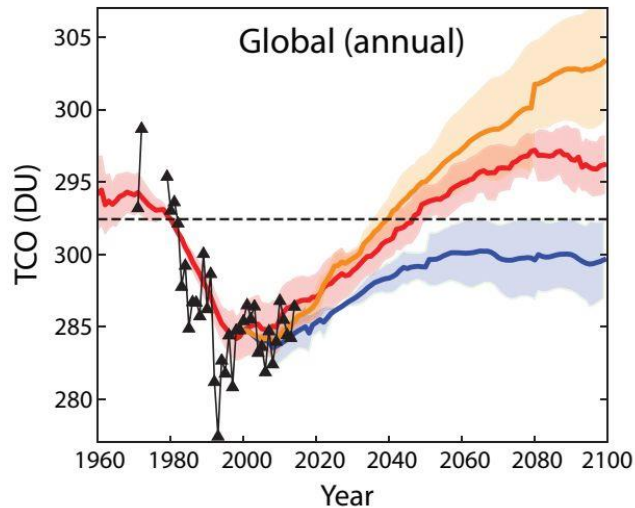


update of Jöckel et al., 2016

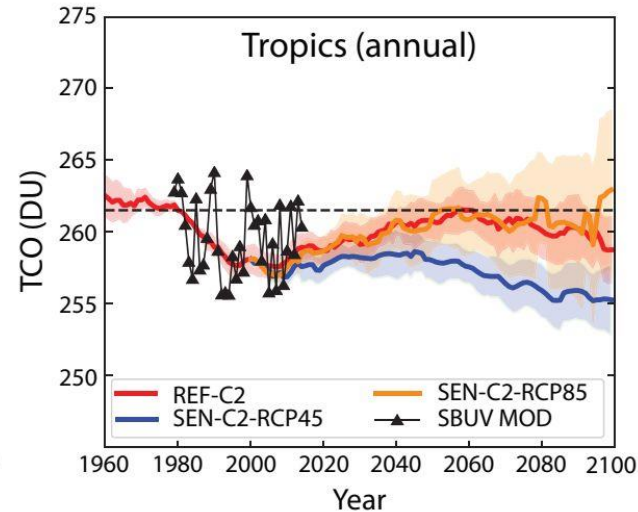


# Ozone projections under different climate change scenarios at middle latitudes, the tropics and the near global mean

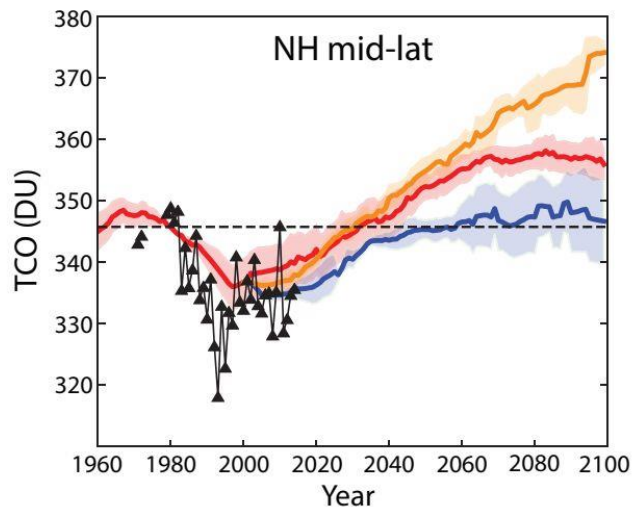
60°S-60°N



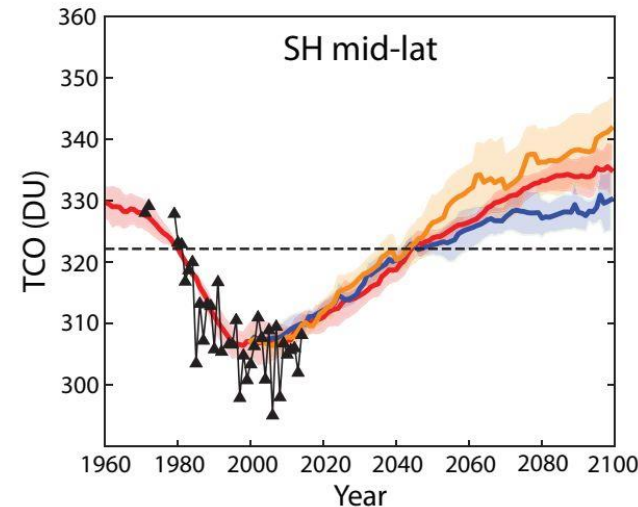
20°S-20°N



30°N-60°N



30°S-60°S

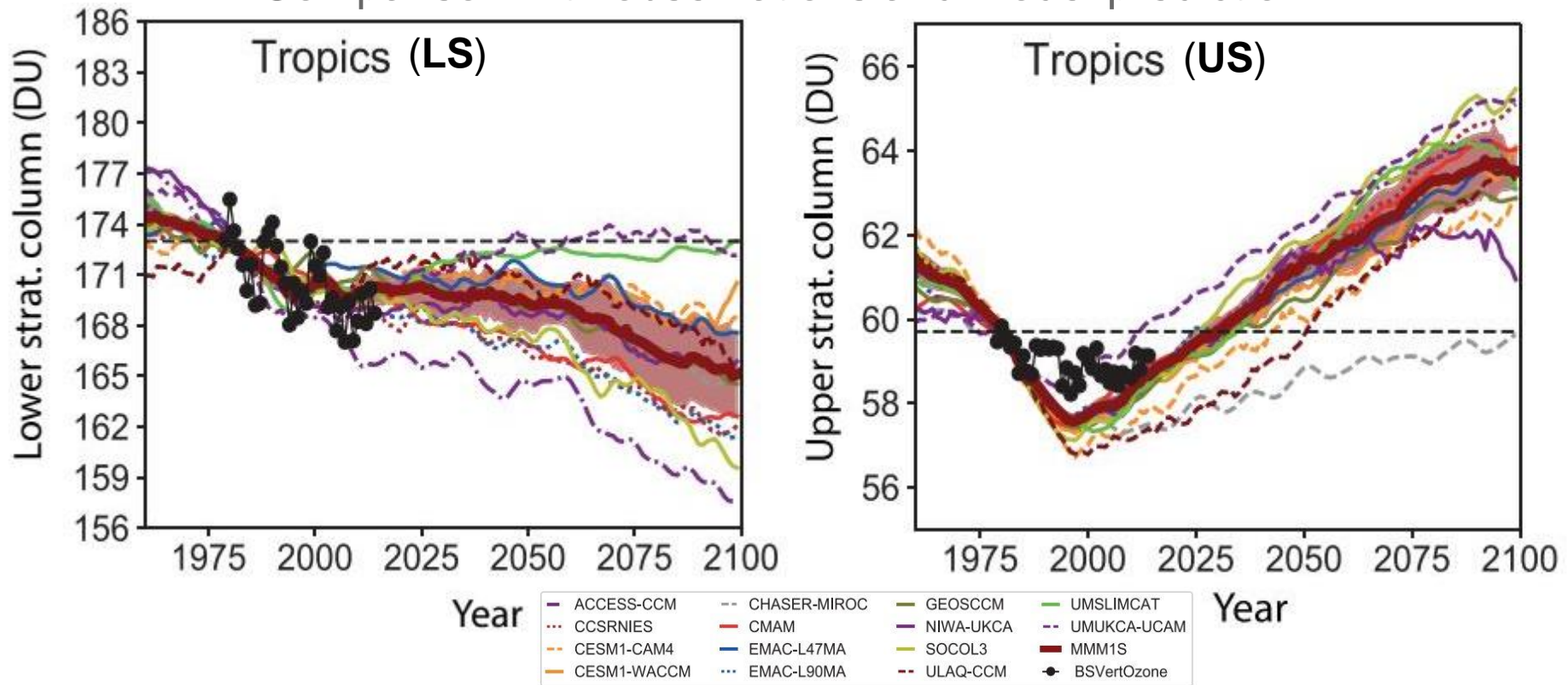


WMO, 2019



# Ozone anomalies (1960-2100): 20°S - 20°N

Comparison with observations and model prediction



Evolution of partial column ozone (DU) (left) for the **lower stratosphere** (LS: tropopause – 10 hPa) and (right) for the **upper stratosphere** (US:  $\geq 10$  h Pa) from the [REF-C2](#) simulations from 14 individual models (different colors), along with the MMM (thick red line). Also shown are estimates of the partial column from the Bodeker Scientific Vertical Ozone (BSVertOzone) database (black dots) (*Bodeker et al.*, 2013).

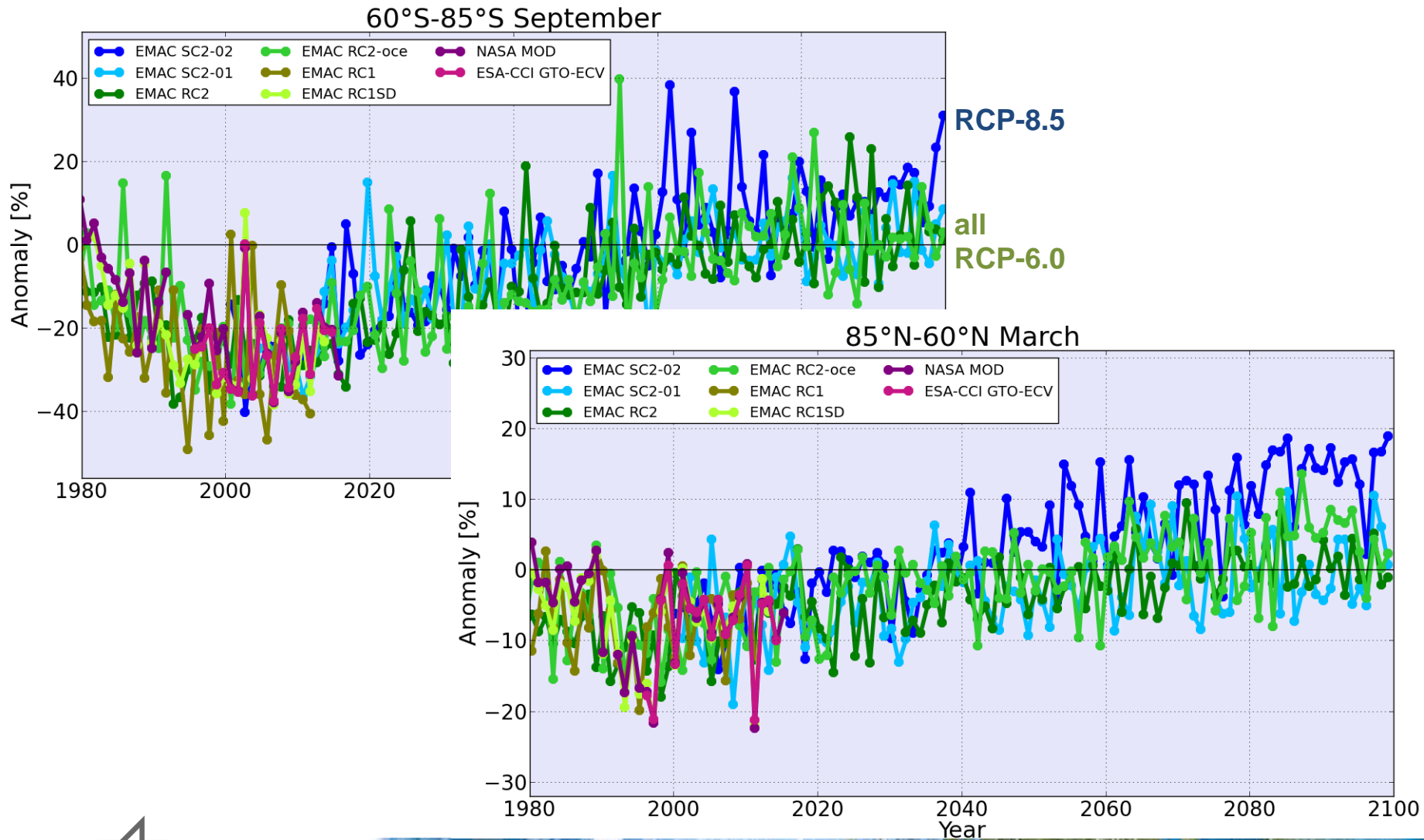
Dhomse et al., 2018





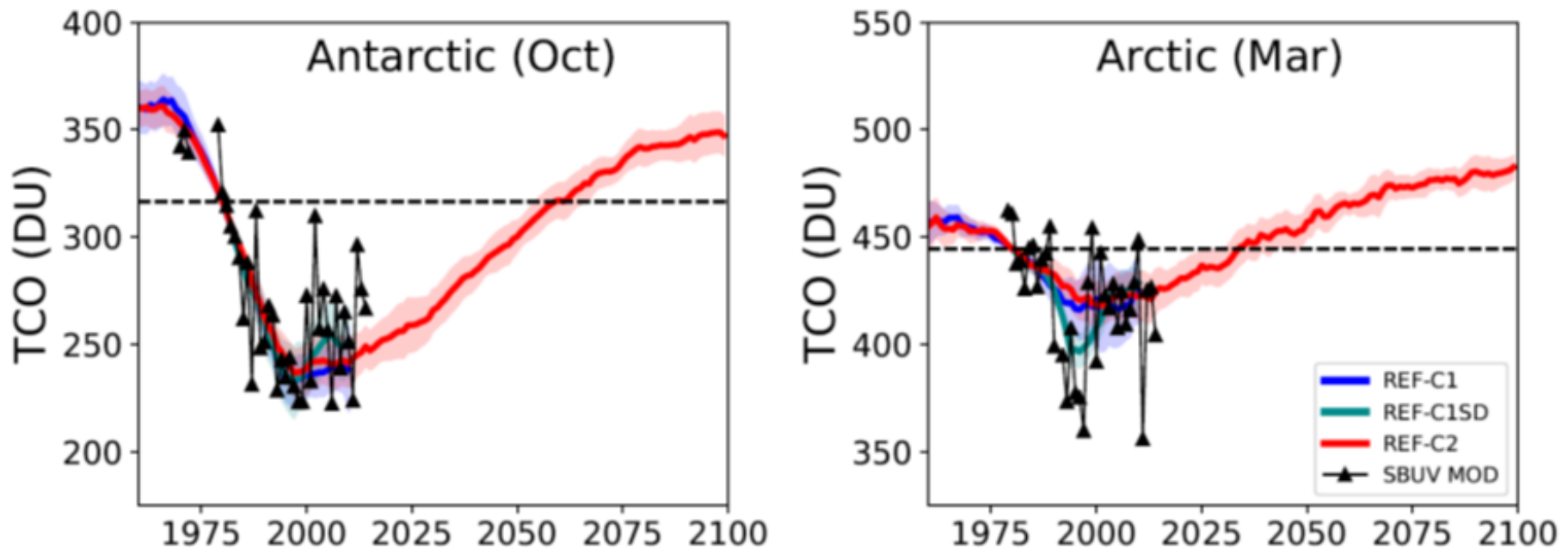
# Ozone anomalies (1960-2100): polar regions

## Comparison of satellite- and CCM-data (EMAC) incl. projections



# Ozone anomalies (1960-2100): polar regions

Comparison with satellite data and model (MMM) prediction

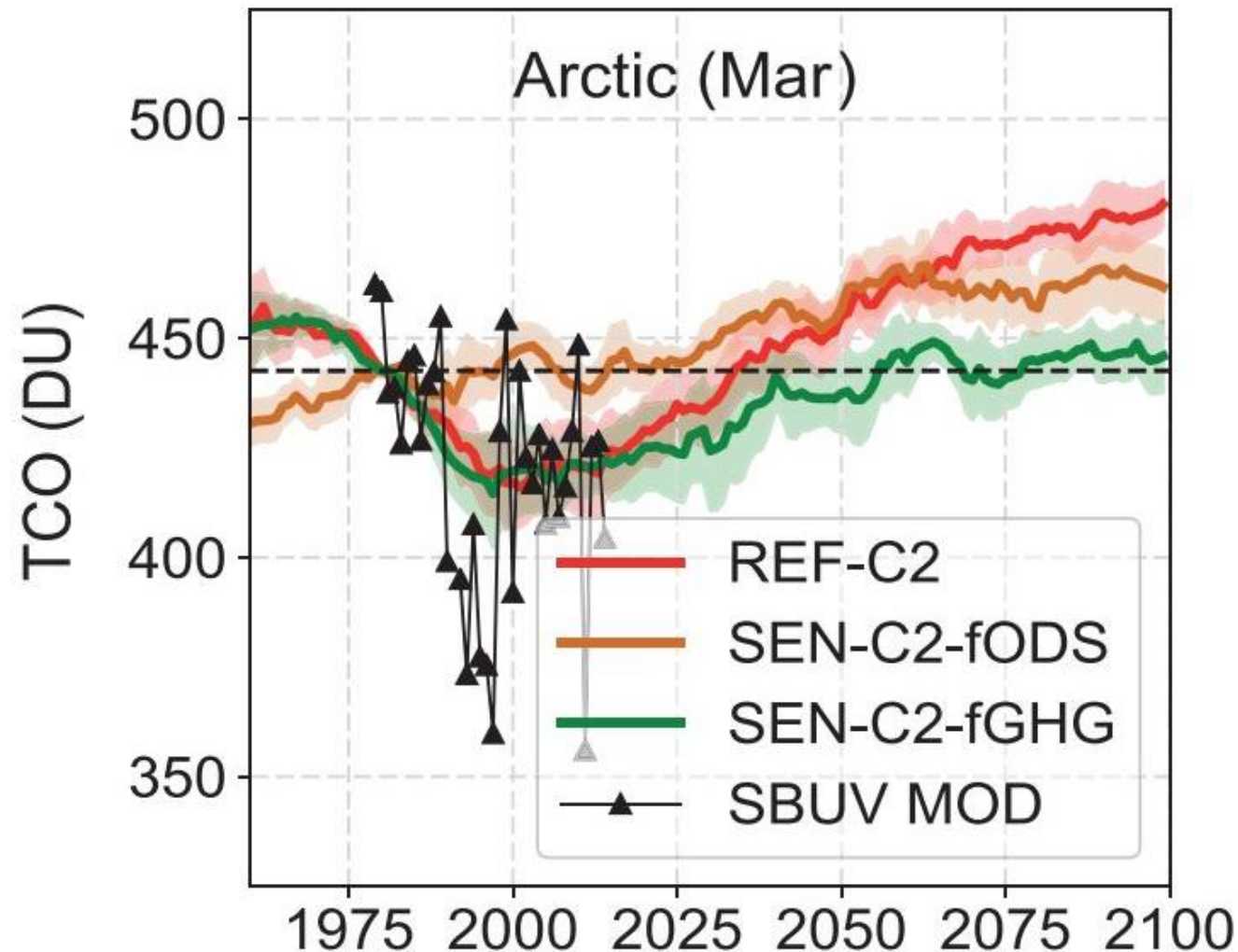


Multi-model mean (MMM) total column ozone (TCO) time series (in DU) from CCMi REF-C1 (blue), REF-C1SD (dark cyan) and REF-C2 (red) simulations for the (left) Southern Hemisphere polar (October) and (right) Northern Hemisphere polar (March) regions. Also shown are the merged SBUV observations. (Fig. 4-18 in WMO, 2019; adopted from Dhomse et al., 2018).



# Ozone anomalies (1960-2100): polar regions

Comparison with satellite data and model (MMM) prediction

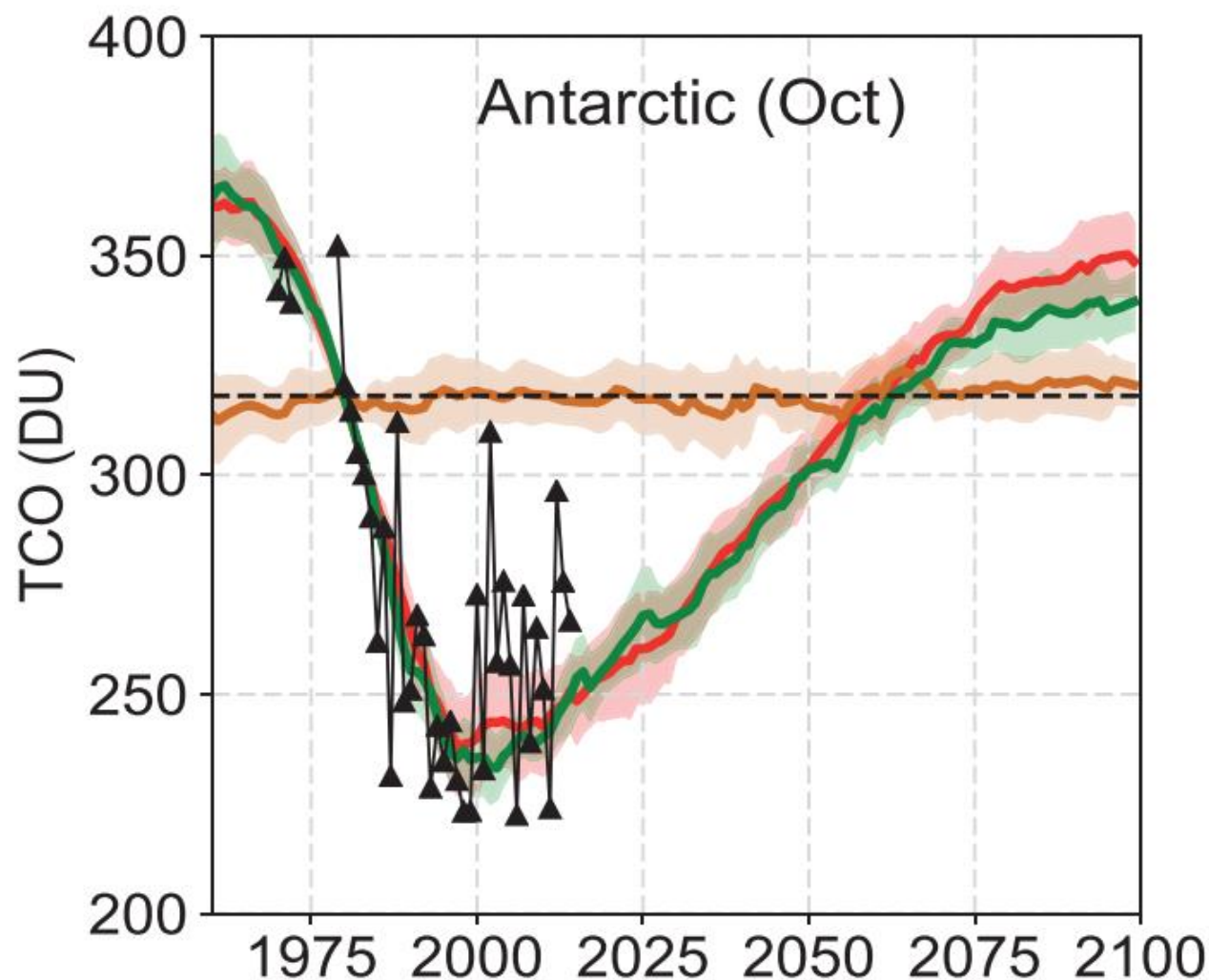
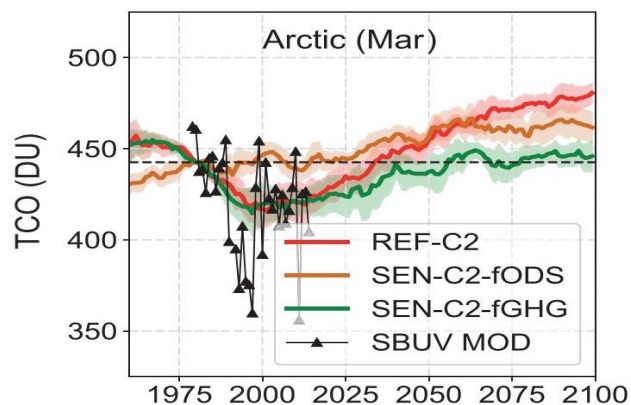


(Fig. 4-19 in WMO, 2019; adopted from Dhomse et al., 2018)



# Ozone anomalies (1960-2100): polar regions

Comparison with satellite data and model (MMM) prediction



(Fig. 4-19 in WMO, 2019; adopted from Dhomse et al., 2018)

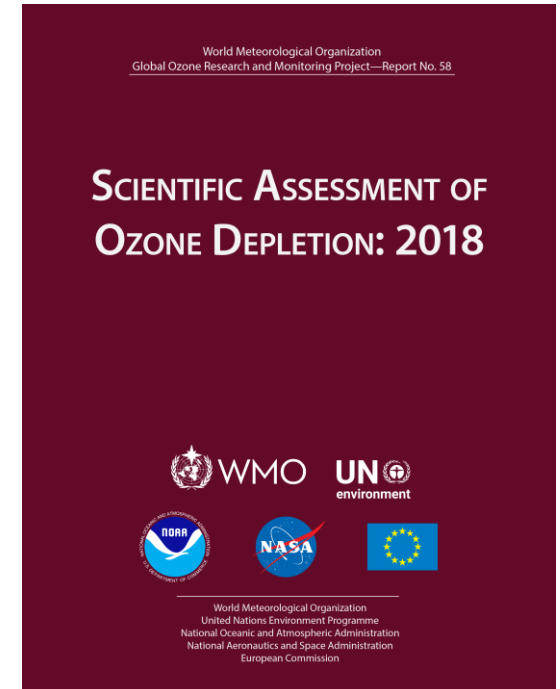




# Concluding remarks

(see also in WMO, 2019)

- There are emerging indications that the Antarctic ozone hole has diminished in size and depth since the year 2000, with the clearest changes occurring during early spring (especially in September).
- In the Arctic, year-to-year variability in total column ozone is much larger than in the Antarctic, precluding identification of a statistically significant increase in Arctic ozone over the 2000-2018 period.



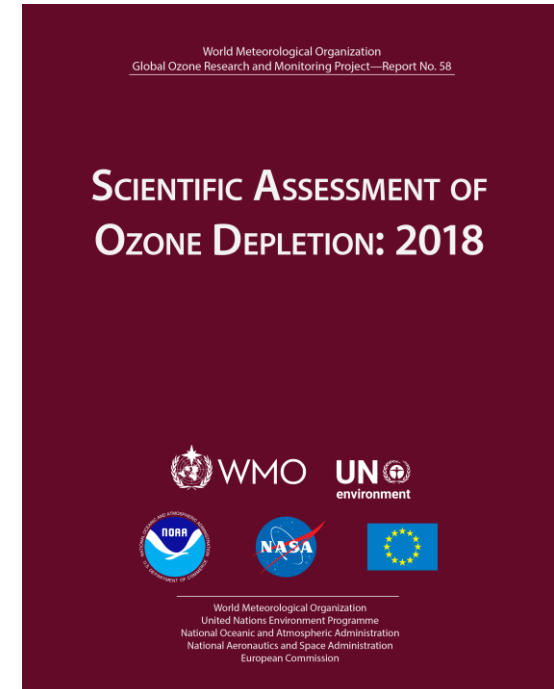
<https://www.esrl.noaa.gov/csd/assessments/ozone/2018/>



# Concluding remarks

(see also in WMO, 2019)

- CCM projections based on full compliance with the Montreal Protocol and assuming the baseline estimate of the future evolution of GHGs (RCP-6.0) have confirmed that the Antarctic ozone hole is expected to gradually close shortly after mid-century (about **2060**).
- The timing of the recovery of Arctic TOC in spring will be affected by anthropogenic climate change. Arctic springtime TOC is expected to return to 1980 values before mid-century (**2030s**).
- In the second half of the 21<sup>st</sup> century CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O will be the dominant drivers of Arctic ozone changes, assuming full compliance with the Montreal Protocol.



## General and final remarks

- The stratosphere plays an important role in the Earth-Climate system. It contains the ozone layer.
- The stratosphere and the troposphere are affecting each other.
- There are strong indications that climate change affects the stratosphere (e.g. cooling of the stratosphere).
- In recent years modelling of the stratosphere achieved major progress. Comprehensive CCMs are established.
- CCMs are able to simulate the dynamic state and variability of the stratosphere as well as the chemical behavior and composition in accordance with observations. Chemistry-climate connections can be investigated in an adequate manner, for instance the evolution of the stratospheric ozone layer in a changing climate.
- CCMs can be used for climate research including the consideration of chemistry feedback processes, e.g. for investigations of chemistry-climate connections. Evaluated CCMs can be used for projections.

